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DETERMINING THE GLOBAL MAXIMUM BIOFUEL PRODUCTION POTENTIAL WITHOUT CONFLICTING WITH FOOD AND FEED CONSUMPTION

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DETERMINING THE GLOBAL MAXIMUM BIOFUEL PRODUCTION POTENTIAL WITHOUT CONFLICTING WITH FOOD AND FEED CONSUMPTION

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ABSTRACT

This study tries to resolve the competition between food and biofuel by balancing the allocation between food and feed areas and biofuel areas for the entire world. The maximum energy production is calculated by determining the theoretical amount of energy that can be grown, once food and feed consumption is taken into account, based on the assumption that unprotected grass and woody lands and forest lands can be converted into cultivated lands. The total optimum land area for biofuel energy, 4,926.49 Mha, consists of corn, rapeseed, sugar beet, sugar cane, and grasses. When considering energy conversion efficiency, the maximum energy production is 520.5 EJ. Of this amount, 5.9 EJ can be identified with food and feed energy and 514.6 EJ can be identified with biofuel energy. This result is a theoretical value to illustrate the potential global land area for biofuel. The biofuel energy production per area of land in this study is calculated to be 0.12 EJ/Mha. With regards to the limitation in the degree of invasion by grass and woody land and forest land areas, if it is not more than 10 percent, the biofuel energy production can serve about 76 percent of energy demand for transportation in 2009. The total optimum land area is about 45 percent of global cultivated land area. Sensitivity analysis shows that the land area of corn, sweet sorghum, sugarcane, grass, and woody crops is sensitive to energy content. The land area of sweet sorghum and soybeans is sensitive to the land area for food and feed consumption. Also, the land area of corn, sugar beet, and sugarcane is sensitive to the potential crop land area. This study, done at the global level, can also apply in a local area by using local constraints.

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CHAPTER ONE

INTRODUCTION

The economy and industry of nations have grown dramatically since the Industrial Revolution. The increase in human consumption has resulted in an increasing demand for resources. Energy is one of the resources that support economic growth and facilitate human lifestyle. Energy is primarily consumed for transportation, heating, cooling, and powering buildings and industrial applications. Information from the International Energy Outlook shows that the global energy requirement for the future continues to increase; from 472 quadrillion Btu in 2006 to an estimated 686.5 quadrillion Btu in 2030 (Figure 1) (Energy Information Administration, 2009). Out of this requirement, oil is currently the main source of energy, representing 42.6 percent of global energy consumption in 2007. Approximately 61 percent of the consumed oil was used for transportation in 2007 (International Energy Agency, 2009). When the demand for oil increases, the market mechanism of supply and demand creates a rational price. This is one of the important factors that make the crude oil prices increase continuously.

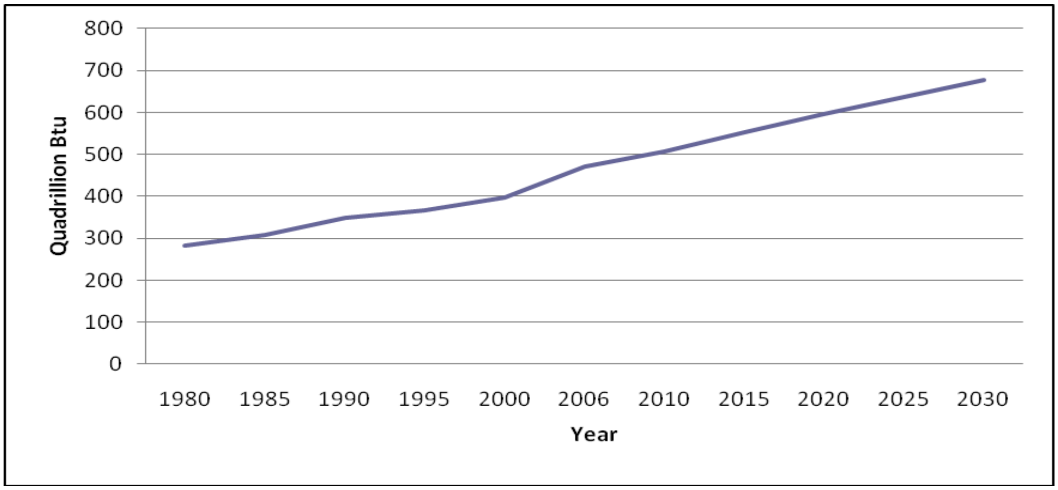

Figure 1.1: Global energy consumption, 1980-2006, with projections to 2030 (Energy Information Administration, 2009)

In terms of the environment, climate change is a common global problem that creates changes in weather patterns. Many studies about climate change indicate that the global average temperature is expected to increase about 1.1 – 6.4 °C from 1990 to 2100 (Intergovernmental Panel on Climate Change, 2007). This phenomenon is caused by greenhouse gases, which mainly consist of CO_2. Carbon dioxide mainly originates from industrial processes, as well as from transportation, which uses fossil fuels as an energy source.

Because of the increasing demand for energy and the price of oil, as well as the concern about the environment and climate change, alternative sources of energy that are renewable and environmentally friendly are of interest to policy makers. Biofuel, an alternative energy, is a potential candidate to replace fossil fuels. Currently, biofuel in the form of ethanol and biodiesel is popular to use as energy for vehicles. Of the total global energy consumption, biofuel represents only 1-2 percent in the transportation sector (Rockefeller Foundation Bellagio Center, 2008).

Today, biofuel demand is increasing rapidly. Many countries promote biofuel as an alternative to fossil fuels and many countries, such as the US and Brazil give numerous incentives to biofuel corporations, farmers, and production industries. This creates a trend of increasing biofuel production. In 2008, the world's total biofuel production was 21,412 million gallons. Of this volume, 17,524 and 3,888 million gallons represent ethanol and biodiesel, respectively (Figure 1.2) (Earth Policy Institute, 2010). The major producers of bioethanol are the United States and Brazil, sharing 87.4 percent of the total, while the European Union produces almost 60 percent of all biodiesel (Fischer et al., 2009).

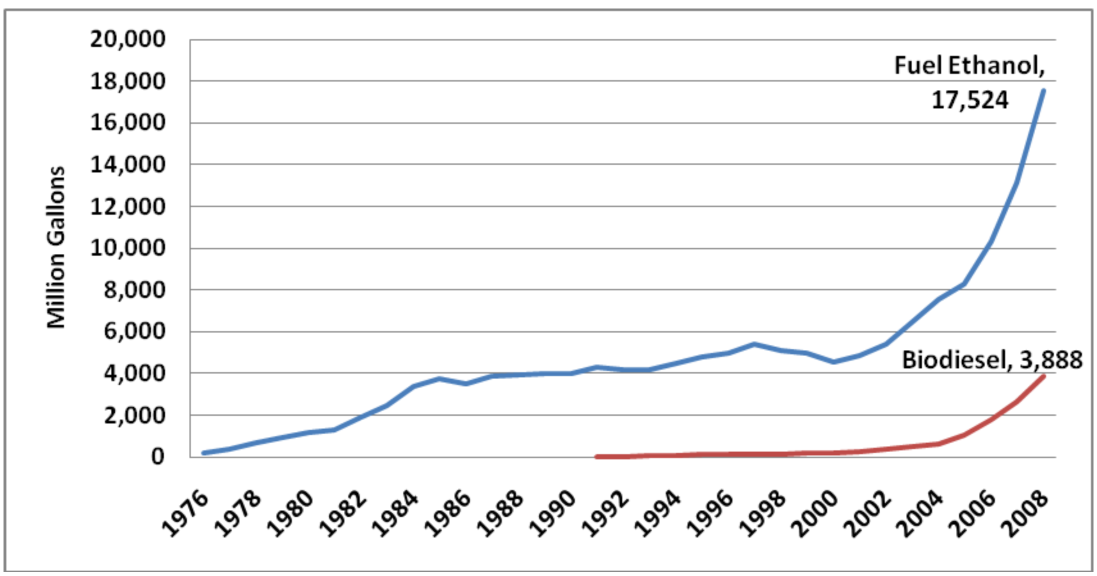

Figure 1.2: Global fuel ethanol and biodiesel 1975 to 2007 (Earth Policy Institute, 2010)

Consequently, more than $4 million was invested worldwide in biofuels in 2007. So, biofuel crops offer a good opportunity chance for farmers to make more money by converting their food crops to biofuel crops in order to serve the biofuel industry. Currently, raw material for biofuel production is from crops that also serve as food, such as corn, palm oil, rapeseed, sorghum, soybean, sugar beet and sugarcane. As a result, along with the rapidly growing global economy and increasing population, there is the possibility of competition between food and biofuel, which creates food insecurity and changing food prices (UNEP, 2009 and Wolf et al., 2003).

However, the agricultural land that produces food is limited. In addition, agricultural yields are not stable and tend to decrease due to natural disasters, climate change, natural resources, and environmental effects, such as soil erosion, salinity, desertification (UNEP, 2009). There are significant data indicating that the annual rate of increase for crop yields tend to decrease. For example, the annual rate of increase in cereal changes from 1.41 percent in 2000-2024 to 0.83 percent in 2050 (Tweeten and Thompson, 2008). The world is facing a problem about food insecurity because of food access equability, so there are large numbers of famines and undernourished people. In the short-term, FAO (2009) estimates that the number of continually hungry people in 2007 increased by 75 million. Between 2003 and 2005 there were 848 million undernourished people due to high food prices. Biofuels are now increasing the problem of food insecurity because some cropland areas may be converted to grow biofuel crops or farmer may allocate more crops to serve as feedstock for biofuels. So, a reduction in land available for food production combined with an increase in the amount of land required for biofuels is inevitable in the near future.

The change of cropland for food to cropland for biofuels is a key problem facing policy makers. The objective of this study is to determine the optimum potential land area of the world to use in biofuel production without affecting food and feed consumption. This study will:

1) Describe the impact to the security of global food production when the demand of biofuel energy increases.
2) Identify the effects to agricultural land and food and feed production given the increasing biofuel demand
3) Calculate the appropriate allocation for each focus crop to be used for biofuels that will cause the least conflict with the land area used for food and feed consumption.

An optimization method that maximizes biofuel energy production without affecting food stability is developed to find the optimal proportion of each crop land area. Although the model does not suggest specific policy incentives, it determines the upper limit of bioenergy that can be obtained from the agricultural system.

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CHAPTER TWO

LITERATURE REVIEW

Presently, the global population is continually increasing, which causes an increased demand for resources, especially food and energy and creates pressure on natural resources and environmental systems, such as biodiversity degradation, climate change, pollution, etc. The energy crisis causes a rapid increase in energy demand, especially for fossil fuels in the transportation sector. Consequently, the world tends to face increasing gas prices. Also, CO_2 emissions from using fossil fuels affect the environment, which causes a climate change problem.

Using biofuel as an alternative energy source plays an important role in solving this problem by reducing pressure on fossil fuels. It was found that biofuel demand has increased rapidly in the past decade. Since the feedstocks for biofuel are from agricultural crops that mainly serve for human consumption, the increase in biofuel demand will affect food production. This phenomenon will affect food prices and change crop land to serve biofuel. Thus, competition between food and biofuel crops is inevitable.

Biofuel Production

The feedstocks for biofuel are generally from edible crops which are sugar crops and starchy crops for ethanol, and oil crops for biodiesel. Those are called traditional biofuels or first generation crops, which have many ways to convert those crops to biofuel products. For sugar crops and starchy crops, fermentation and distillation are techniques to transform them to ethanol, while oil crops use extraction and esterification to convert to biodiesel (UNEP, 2009). The crops in this group are shown in Table 2.1.

In addition, there are some crops, which are composed of cellulose, hemicellulose or lignin that can be converted to ethanol, for example woody trees, grasses, and also agricultural residue such as leaves, straw, stocks etc. The feedstocks from this group are called second generation biofuels. There are two ways to convert them into ethanol; 1) biochemical techniques: cellulose, hemicellulose or lignin is broken by enzymes into sugar and then sugar is converted to ethanol by the same process as first generation biofuels which are fermentation and distillation. 2) thermo-chemical techniques; gasification and pyrolysis are used to convert raw material into a synthesis gas which can be developed to other forms e.g. biomass-to liquids, Fischer-tropsch diesel (Ravindranat et al., 2010). Moreover, in further step, biofuel can be produced from algae that give high energy yield and need small space for processing, called third generation biofuels. For example, algae are the potential feedstock for biofuel that will require less land area than previous generations of biofuels. One GJ energy production from algae requires only two square meters of land area, while corn and rapeseed need 133 and 383 square meters (Singh et al., 2011). This can help to decrease conflicts with land use.

Table 2.1: Biofuel feedstock and production

Biofuels	Crop Types	Feedstock	Production
First Generation	Sugar crop	Sugar cane, Sugar beet, Sweet sorghum	Ethanol
	Starchy crop	Corn, Cassava, Wheat, Barley, Rye, Potatoes	Ethanol
	Oil crop	Rapeseed, Palm oil, Soybean, Sunflower, Peanut, Jatropha	Biodiesel
Second Generation	Cellulosic crop	Switchgrass, Miscanthus Willow, Poplar, Silver Birch, and agricultural residue	Ethanol
Third Generation	Algae fuel	Algae	Biodiesel, Bioethanol, Biobutanol

Source: UNEP, 2009 and FAO, 2008

Currently, the first major countries which produce biofuel are the U.S.A., Brazil, and European Union (Table 2.2). For bioethanol, the highest amount of production is from the U.S.A. which mainly comes from corn, while Brazil is from sugarcane. Both countries produce bioethanol almost 90 percent of the world production of bioethanol **(**FAO, 2008 and OPEC Fund for International Development, 2009). The European Union produces the highest amount of biodiesel which is from rapeseed while the U.S.A. is second producing from soybean. The U.S.A. and the European Union countries share almost 80 percent of the global biodiesel production **(**FAO, 2008 and OPEC Fund for International Development, 2009). Corn, sugarcane, rapeseed and soybean are popular to use as feedstock for global biofuel. The details are shown in Table 2.2.

Table 2.2: Global production for biofuel distributed by countries.

Country	Production (Million liters)	Percent	Feedstocks
Ethanol			
US.	26,500	50.95	Corn
Brazil	19,000	36.53	Sugar cane
European Union	2,253	4.33	Sugar beet
Canada, China, India, etc. and others	4,257	8.18	Wheat, Cassava, Sweet sorghum
Total	**52,010**	**100**	
Biodiesel			
European Union	6,109	59.86	Rapeseed
United State	1,688	16.54	Soybean
Southeast Asia (Malaysia and Indonesia)	739	7.24	Palm oil
Canada, China, India, and others	1,669	16.35	Sunflower, Peanut, Cottonseed, Coconut, Olive
Total	**10,205**	**100**	

Source: FAO, 2008 and OPEC Fund for International Development, 2009

Thus, we can assume that corn, sugarcane, sugar beet, rapeseed, soybean, sweet sorghum and palm oil can produce almost 90 percent of biofuel products throughout the world. So the global areas for those major biofuel crops are represented as the area for the biofuel crop.

Biofuel Impact and Land Use Change

Biofuel is a potential alternative energy especially for the transportation sector where environmental concerns and energy security are concerned. Due to this reason, biofuel production is increasing continuously (Cherubinia et al., 2009). Considering the life cycle of biofuel production, it can reduce greenhouse gases (GHG) by about 80 percent when compared with fossil fuels (UNEP, 2009). In 2009, global greenhouse gas emissions were reduced by about 87.6 and 35.9 million tons, due to the production of 73.7 billion tons of ethanol and 16 billion tons of biodiesel, respectively. The total production of ethanol and biodiesel caused GHG emissions to be reduced by about 57 percent (Global Renewable Fuels Alliance, 2009).

Although using biofuel as energy in the transportation sector can directly reduce GHG emissions, land use changes due to the demand for biofuel production and the need for more land area for biofuel crops, created by invading forest areas, cause an increase in GHG emissions (Timilsina and Shrestha, 2010). Biofuel production affects land use in two ways; 1) direct change; the current cultivated, pasture, and forest lands are switched to grow biofuel crops and 2) indirect change; land areas which have never been cultivated are used for food crops (Borjesson and Tufvesson, 2010). In general, a range of 49 – 90 percent of greenhouse gas emissions is reduced by using biofuel. If we consider the land use change impacts from biofuel crop production, the percent of GHG will be increased by 1-102 percent (Timilsina and Shrestha, 2010).

In addition, the impact of the increase in biofuel production can be illustrated in terms of carbon payback time. This number will show how many years are required in order to compensate for the environmental problems caused from converting land to biofuel crops (Timilsina and Shrestha, 2010). The estimation shows that 48 years are needed to relieve the Conservation Reserve Program land (CRP) that was switched to corn land area for ethanol production in the U.S.A. Also, over 300 and 400 years, respectively, are needed for the replacement of rainforest with soybeans in the Amazon area and for palm oil in Indonesia and Malaysia. Overall, the conversion of forest needs 75-93 years payback time, while over 600 years for converted peatland (Timilsina and Shrestha, 2010). Thus the reduction of GHG emissions in biofuel production is reasonable as long as land use changes are not taken into account.

The increase in food consumption directly relates to agricultural production, causing the need for harvested land to increase. The increase in biofuel production is one factor that is criticized because it causes the land allocation to change. FAOSTAT (2010) reports that more than half of global land areas are pasture lands and forest lands, while croplands for agricultural production is approximately 11 percent (1.43 billion ha). The global food consumption can be divided into four purposes: for food, feed, seed, and waste (FAOSTAT, 2010). The OPEC Fund for International Development (2009) reports that the world cultivated area is about 1.6 billion hectares, which is composed of 60 percent food crop area, 33 percent for feed production and 7 percent for seed and waste

(Figure 2.1). Waste refers to the crop production that is lost in the conversion process as well as the inappropriate transportation and storage of the crops.

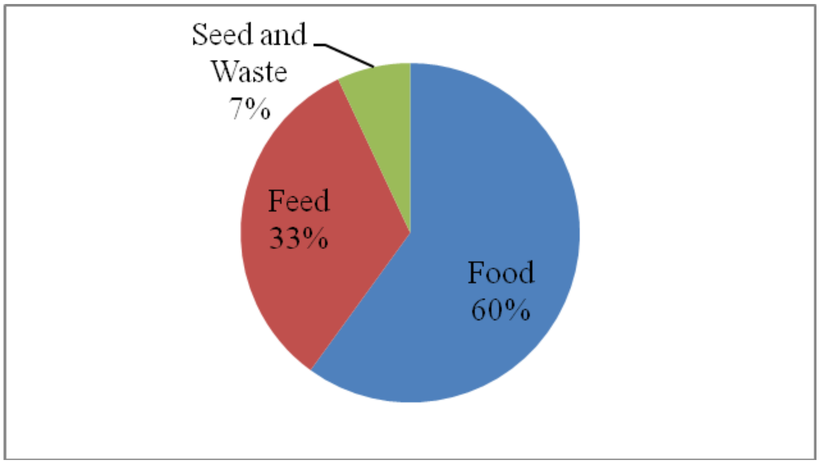

Figure 2.1: Percentage of cultivated area by different purposes (FAOSTAT, 2010)

When considering the six major biofuel crops, which are sugar cane, maize, rapeseed, soybeans, palm oil, and cassava, the cultivating area for biofuel production is approximately 25 million hectares or 1.6 percent of the global cultivated crop area in 2007. Although biofuels represent a small fraction of current agricultural land, the demand for biofuels is increasing dramatically. The OPEC Fund for International Development (2009) forecasts biofuel demand through the year 2030 will cause the cultivated area for biofuels to increase to approximately 65- 150 million hectares, or 4-9 percent of total cultivated land. Moreover, UNEP (2009) estimates that the demand for biofuel crop area will increase to approximately 1.67 billion hectares in 2050, which exceeds the global cultivated area. In addition to biofuel demand, food demand also increases continuously due to the population growth. The competition between food and biofuel crops is inevitable.

Forest and pasture lands are target areas that are easy to be converted, especially for biofuel crop. These areas usually are affected especially in developing countries such as countries in Africa and South America that need more land areas for biofuel crop to generate more income. However, land use change for forest and pasture is not only due to biofuel production but also due to food production. The conversion of forest and pasture in some countries in Asia such as India and China are caused by the food demand that requires more land area for cultivation (Timilsina and Shrestha, 2010).

Since corn is the main feedstock for bioethanol in the United State, farmers tend to switch from other crops to corn (Searchinger et al., 2008). The data from FAOSTAT (2010) show that from 2000 to 2009, the crop land area of corn and soybean in United State increased by about 9.5 and 5.47 percent, respectively, while crop land areas for soybean and sugarcane in Brazil increased by approximately 60 and 80 percent, respectively. It is possible that pasture and forest lands were converted to these crops, rather than to other crops. Surely, increases in biofuel fuel crop area will affect the crop land area for food. If we need to have enough land for food, invading pasture or forest lands that provide a benefit to the environment is inevitable.

However, many researchers argue that biofuel production is not the major cause for land use change. There are some land areas that can grow biofuel crops without threatening cropland for food such as grazing land, marginal land, fallow land, even though, the crop yield from those areas cannot provide high productivity (Johansson and Azar, 2007). For example, the increase of biofuel production in India does not affect food production. Since 1989, croplands in India are still the same, although Indian government has a policy to promote biodiesel. The key success factor of this case is that this policy emphasizes biodiesel from non-edible crops and encourages growing biofuel in marginal land, fallow land and wasteland (Ravindranath et al., 2010). Policy mechanisms like these are also used in Europe (Ajanovic, 2010). However, the increasing of marginal land for biofuel production may affect environment and natural resources. Since marginal lands are the less productive land, using them land for biofuel production will require more fertilizer and irrigation (Simpson et al., 2008).

Moreover, there are several methods to limit the crop land area for biofuel. Cellulosic feedstocks that come from non-edible biofuel crop and agricultural and forest residue can reduce impact on land use change (Timilsina and Shrestha, 2010). For example, using bioethanol by-product to produce biofuel in the European Union helped to reduce the area for growing corn by at least 0.7 million ha. Also, crop residue that is used for livestock feed can be used as feedstock for biofuel, therefore less crop land area will be needed for biofuel (O¨zdemir et al., 2009). In addition, Service (2007) supported this concept by showing the advantage to use crop residual. Since corn is the main feedstock for bioethanol in U.S.A., if all residual from corn is used, it can decrease the impact on food production and land use conversion. This volume can replace about one third of the fossil fuel in the transportation sector. In addition, the advanced technology for agriculture can improve crop productivity. Farmers can get more yield than usual based on the same size of crop land area. Therefore, increasing agricultural production can reduce conflict between food area and biofuel area (Nonhebel, 2007).

UNEP (2009) predicts land requirements for biofuel based on previously performed studies. Focusing on first generation biofuel, the land requirements ranges from 35-166 and 166-476 Mha, in 2020 and 2050, respectively. The fluctuation depends on feedstock type, crop yield, geographic considerations, and other assumptions. The OPEC Fund for International Development (2009) reports cultivated land requirements for first generation biofuel by using an ecological-economic modeling approach that considers many factors such as crop land availability, land suitability, crop yield, climate zone etc. The result shows that cultivated land for biofuel crop will need more than 27 and 37 Mha, in 2020 and 2030, respectively.

Competition between Food and Biofuel Studies

There are many studies about the competition between food and biofuel that are related to energy production and land area allocation for biofuel crops with different approaches (Table 2.3). Most studies estimated the land area for biofuel by calculating the surplus area from the area for food and feed consumption by using the data related to food production such as food demand, food production and the growth of population etc. For example, Gurgel et al. (2007) estimate agricultural land area by using the computable general equilibrium framework based on biofuel crop yield and biomass conversion technology. In a similar manner, Wolf et al. (2003) and Fischer et al. (2009), calculated the agricultural land areas for biofuel by analyzing existing data such as food demand, agricultural production etc. Also, Smeets et al. (2007) calculated the surplus area for biofuel crop by using the Quickscan model, which is an Excel spreadsheet based on data such as population growth, food consumption and food production biomass potential, agricultural land available etc.

However, Nonhebel (2005) used the footprint concept, which is different from the previous studies to estimate land requirement for food and biomass in units of area per person per year. This unit value can be used to calculate the total land area for biofuel by multiplying by population.

The types of data used in each study are based on food demand, agricultural production, and population growth rate. Considering the total land area predicted for biofuel using data, Gurgel et al. (2007) reports a range from 419 to 1,668 Mha, which is similar to Nonhebel (2005) who reports from 511 to 13,433 Mha when his results are converted to the same units. However, none of these studies used an optimization approach to determine the optimum land area for biofuel. Optimization can identify the area for each crop type which will be helpful for policy makers to use in land allocation management.

Table 2.3: Summary studies related to the competing between food and biofuel

Studies	Methods	Results
Gurgel et al.(2007)	Computable General Equilibrium (CGE) framework by using significant data on the energy sector and land use at the global level between 2010-2100 based on 2 scenarios: normal policy and environmental concern policy.	Focusing on 2050: Normal policy: energy range is 35 to 39 EJ and land area range is 419 to 476 Mha, Environmental concern policy: energy range is 122 to 134 EJ and land area range is 1461 to 1668 Mha.
Wolf et al. (2003)	The data about food demand and food supply were used to calculate the areas for biofuel at the global level based on different scenarios such as crop productivity, population growth rate, and consumption pattern by forecasting at the global level through 2050	About 45 percent of global crop land area contributed to biofuel production based on good agricultural practices. Without the good agricultural technology, there is not enough land for biofuel crop.
Nonhebel (2005)	Using footprint concept to calculate land requirement per person per year for food and biomass based on 2 factors in	In the wealthy situation, the land requirement for biofuel crop is 7,410 m^2/person/year and when the unfortunate

Studies	Methods	Results
	different scenarios such as crop productivity and consumption pattern at the global level of 2005	situation the land requirement for biofuel crop will be at 19,444 m^2/person/year.
Fischer et al. (2009)	Data of food demand and agricultural production were used to analyze the areas of agricultural land that can be interpreted as the surplus land area for biofuel based on 3 scenarios: current policy, environmental policy and energy policy in Europe between 2000-2030.	In 2030, the land available for biofuel will be 18, 22, and 30 percent of agricultural and pasture land area, based on environment, current, and energy policy, respectively.
Smeets et al. (2007)	The Quickscan model was used to analyze data which composed of population growth, food consumption and food production biomass potential, agricultural land available etc. to determine the surplus area for biofuel crop. It was conducted at the global level based on 4 scenarios in different level of agricultural technology through 2050	The biofuel energy production on surplus crop land range in 215–1272 EJ/yr, depending on agricultural practice.

Various studies applied the optimization approach to study the issues related to biofuel energy (Table 2.4). It is usually used for the economic aspect. For example, Parker et al. (2010) used an optimization model to determine the maximum profit of biorefineries throughout the biofuel life cycle product. Similarly, Rentizelas et al. (2009) used it to maximize the financial yield of the investment for an energy conversion facility and district heating and cooling network. Huang et al. (2010) and Callesen et al. (2010) used an optimization model to minimize the cost of the entire supply chain of biofuel based on different factors.

A multi-criteria optimization model was used by Ayoub et al. (2009) to design and estimate the integrated system of bioenergy production supply chains by considering the social, environmental and economical factors. Also Rentizelas and Tatsiopoulos (2010) use a hybrid optimization method to find the optimum location and investment cost of bioenergy for district energy.

Although there is some application of the optimization model to aspects of the biofuel issue, no study use this model in resource allocation. Only the study of Callesen et al. (2010) mentioned land area as a constraint in the model. Optimization provides an advantage for use in land allocation because the optimum value of land area can be determined under many constraints; therefore, it will be used in this study.

Table 2.4: The studies about biofuel using optimization approach as method

Studies	Title	Methods
Parker et al. (2010)	"Development of a biorefinery optimized biofuel supply curve for the Western United States"	A mixed integer-linear optimization model is used to determine the maximum profit by finding the optimal locations, technology types and sizes of biorefineries throughout the biofuel life cycle product.
Huang et al. (2010)	"Multistage optimization of the supply chains of biofuels"	A mathematical model is used for strategic planning of future bioethanol supply chain systems by minimizing the cost of the throughout the supply chain in order to meet the constraints such as the demand resource and technology
Rentizelas et al. (2009)	"An optimization model for multi-biomass tri-generation energy supply"	Examining the maximum benefit from the investment based on supply chain, the energy conversion facility and the local heating and cooling network.
Callesen et al. (2010)	"Optimization of bioenergy yield from cultivated land in Denmark"	Linear programming was used to minimize cost for biofuel supply from the annual crops on arable land, short rotation forestry (willow) and plantation forestry. Food and feed supply and nitrogen balance are the constraints.

Studies	Title	Methods
Rentizelas et al. (2010)	“Locating a bioenergy facility using a hybrid optimization method”	A hybrid optimization method is used to find the optimum location with the optimization of operation and investment cost of a bioenergy plant for district energy.
Ayoub et al. (2009)	“Evolutionary algorithms approach for integrated bioenergy supply chains optimization”	Multi-criteria optimization model was used to design and estimate the integrated system of bioenergy production supply chains at the local level by considering the social, environmental and economical factors.

Uncertainties of Data Using in the Model

The results from the optimization depend on the input data which often have uncertainties. Uncertainties may distort the results from the model. The major uncertainties for a study of the competition between food and biofuel are, for example, food demand, agricultural practice, energy content, and agricultural land available (Dornburg et al., 2008). Each of these is noted below.

First, food demand is directly related to the human consumption pattern and the population growth rate. The human consumption depends on the life style of the individual. People in developed countries tend to consume more than people in developing countries. FAOSTAT (2010) reported that the global average for food demand is 2797.64 kcal per capita per day in 2007, while the demand of food in some parts of the world such as Africa and Asia is below the global average. On the other hand, the food demand in Europe, Americas and Oceania is above the global average. Also population growth affects the global food demand. Currently, the global population still increases continuously, although the growth rate is predicted to decrease from 1.89 percent in 1989 to 0.36 in 2050 (UN, 2010; Tweeten and Thompson, 2008). The consumption and the population growth affect the uncertainties of the food demand (Table 2.5)

Table 2.5: Annual rate of increase for food and feed demand

Crop	**Annual food demand increasing rate (percentage)**	
	2001-2030	**2030-2050**
Cereals	1.2	0.6
Vegetable oil	2.3	1.6
Sugar crop	1.3	0.7
Feed	1.6	0.8

Source: FAO, 2006

Second, agricultural practices such as technology, fertilizer, irrigation etc. are related to the alteration of agricultural yield. Dornburg et al. (2008) report that good agricultural practice helps to increase the biofuel potential by 200-1400 EJ/year and a 12.5 percent increase for biofuel crop yield can increase biofuel potential by 40-60%. The annual crop yield for biofuel crop increases because of the agricultural practice, although the rate is expected to decline (Table 2.6).

Table 2.6: Annual rate of increase for crop yield by crop type

Crop	**Annual increase crop yield rate (percentage)**		
	2000-2024	**2025-2049**	**2050**
Cereals	1.41	1.04	0.83
Vegetable oil	0.48	0.43	0.39
Sugar crop	0.93	0.76	0.64

Source: Tweeten and Thompson, 2008

Third, different crop types provide different amounts of the energy yield. In general, cellulosic crops such as grasses and woody trees provide more energy yield than edible biofuel crops such as starch, sugar and vegetable oil crops (Dornburg et al., 2008). In addition, the amount of energy content from biofuel crop depends on crop production yield and energy yield that can lead to an uncertainty for energy content (Table 2.7).

Table 2.7: Energy content range for the selected crops

Crops	Energy content range (GJ/ha)
Edible crops	
Corn	126 - 331
Palm oil	253 - 422
Rapeseed	40 - 96
Sweet Sorghum	132- 206
Soybean	36 - 60
Sugar Beet	452 - 572
Sugarcane	333 - 582
Cellulosic Crops	
Grassss (Switchgrass, Miscanthus)	141- 338
Woody trees (Silver Birch, Poplar, Willow)	92 - 181

Source: Miller, 2010

Finally, agricultural land tends to be degraded due to many factors such as soil degradation and erosion, nutrient loss, etc. The main cause is from improper agricultural practice such as over use of agricultural chemicals (UNEP, 2007). The degradation and improvement of land area is categorized by land use type between 1987–2006 in Table 2.8.

Table 2.8 Changes in land area by land use type between 1987 – 2006

Land	**Loss** (1,000 km^2/year)	**Gain** (1,000 km^2/year)	**Net change** (1,000 km^2/year)
Forest	-130	57	-73
Grass/woody	-26	50	24
Agricultural	-79	108	29

Source: UNEP, 2007

The uncertainties mentioned above should be of concern in any study about the competition between food and biofuel production. In many research studies, sensitivity analysis and scenario approach are conducted in the study to minimize the effect of uncertainties. Most studies use the scenario approach to examine uncertainty. For example, Gurgel et al. (2007) and Fischer et al. (2009) set the scenario based on different policies. Wolf et al. (2003) did not consider the changing of policies but focused on the uncertainty of crop productivity, population growth rate, and consumption pattern, as did Nonhebel (2005).

Compared to the literature reviewed, this research deals with the uncertainties problem in a different approach. The sensitivity analysis is applied to examine the uncertainty of energy content, land area for food and potential land area.

Using Optimization Model for Solving Food and Fuel Competition

This study is different from other studies because the optimum land area for biofuel crop is identified, based on the maximum energy production by using an optimization approach. Because of a limit on natural resources such as arable land area, the optimization approach is a good tool for this study to allocate resources in order to the maximize energy production. This method is usually applied in the business sector to develop the production process for maximizing profit. The maximum point or the minimum point is evaluated in a mathematical way on an objective function. Linear programming is an effective method to use for solving this problem. A linear objective function and linear equations or inequations constraints are created (Kanniappan and Ramachandran, 1998). The main components of the optimization model are 1) objective function: there are two types of model equations, i.e. to maximize and minimize objective function that show the mathematical equation with unknown variables, 2) decision variables: the unknown variables that change while finding the best value that satisfies the objective function, 3) constraints: the mathematical equation that represents the limitation, and 4) variable bounds: the possible value that will relate to the objective function (Chineck, 2001). In addition, sensitivity analysis is used to deal with the uncertainty. This way differs from other studies that usually use scenarios to deal with the uncertainty.

The results from this study will illustrate the amount of the global potential land area for biofuel crops. Moreover, the biofuel crop types and their land areas that should contribute to biofuel production are identified. This is a unique study that is useful for the planning of the global biofuel production.

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CHAPTER THREE

METHODS AND DATA SOURCES

This research was conducted at the global level to determine the appropriate proportion of biofuel crop land area without conflicting with food production in order to get the maximum food and biofuel energy. The optimization approach was used to solve this problem. Linear programming is an effective tool to use for addressing this problem. An objective function and constraints were required to calculate the optimum results. The objective of this study is to maximize the energy product by determining the proportion of land area of various biofuel crops which are divided into edible and non-edible crops. The constraint is to ensure adequate crop land area for food for the global population and livestock for the maximum food energy. The constraint is determined by the amount of the available agricultural land and the amount of land needed to provide adequate food supply. The decision variables are the amount of land area that is dedicated to biofuel crops. The study framework is shown in Figure 4.1.

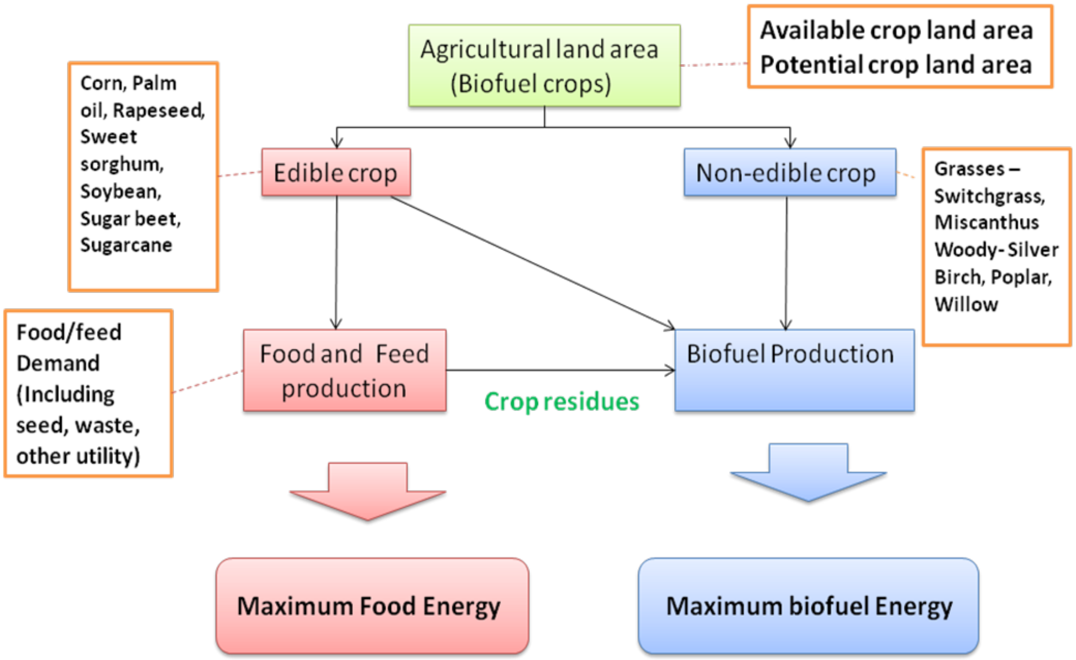

Figure 3.1: The study framework for the maximum food and biofuel energy

3.1 Selected Biofuel Crops

In this study, the target biofuel crops are selected by considering production proportion and energy content. About 92 percent of the global ethanol is produced from corn, sugarcane and sugar beet; approximately 84 percent of biodiesel is produced from rapeseed, soybean and palm oil (FAO, 2008 and OPEC Fund for International Development, 2009). We can assume that corn, sugarcane, sugar beet, rapeseed, soybean, and palm oil produce almost 90 percent of biofuel production throughout the world. These production proportions are shown in Figure 3.1 and 3.2. Moreover, these biofuel crops have high potential in terms of energy content.

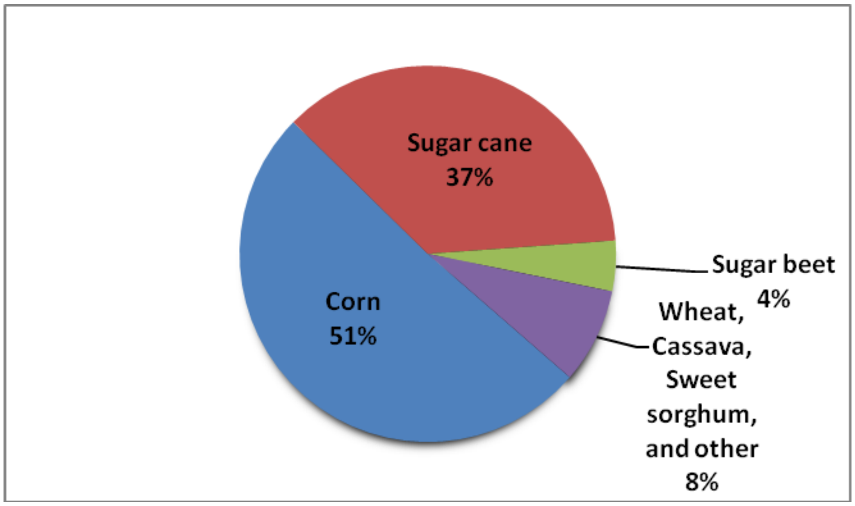

Figure 3.2: Global ethanol productions by biofuel crops (FAO, 2008 and OPEC Fund for International Development, 2009)

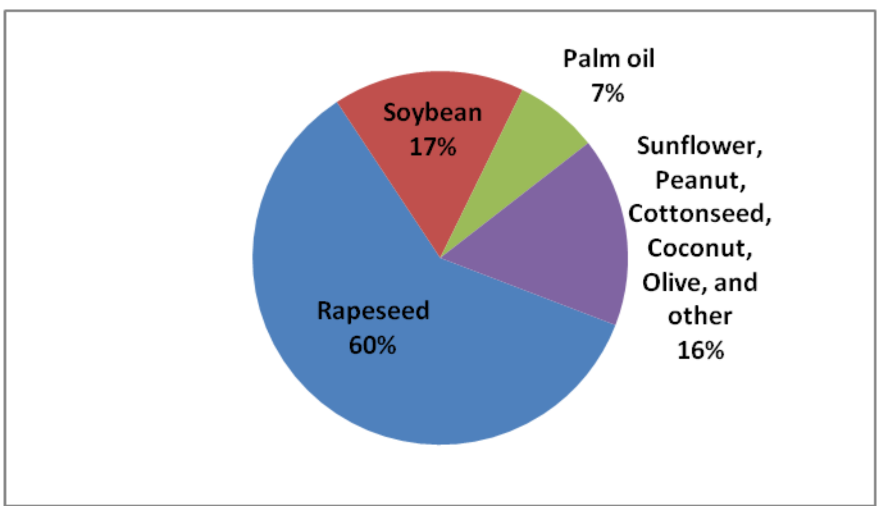

Figure 3.3: Global biodiesel productions by biofuel crops (FAO, 2008 and the OPEC Fund for International Development, 2009)

In addition to those biofuel crops, there are potential future energy crops that have high energy content, grain yield and ease of cultivation. For example, sweet sorghum and some feedstocks composed of cellulose can be converted to ethanol, such as woody trees, grasses, and also agricultural residue (Rajvanshi and Nimbkar, 2003).

There are two concerns in this study:

1) Some potential biofuel crop types are not included in this study because of limitations in production and data support. For example, jatropha is a potential vegetable oil, but the proportion of global use is still small due to many limitations, such as uncertainty in the product yield, toxicity, and economic aspects.

Cassava is a potential crop for ethanol production, but it is mainly used for food in Africa and Latin America, while Asia and Europe use it for livestock and starch industries. Also, some cereal crops, such as wheat, barley and rye provide more economical value for human consumption than for biofuel. Thus, they are not suitable to be feedstock for energy purposes (FAO, 2008).

In addition, other seed oils, such as, sunflower, peanut, cottonseed, coconut, and olive are mostly used in the local community. Their global production is very small in proportion to palm oil, soybean, and rapeseed (OPEC Fund for International Development, 2009). Also, in terms of future biofuel feedstock, algae are potential feedstock for biofuel that need small land areas. One GJ energy production from algae needs land area of only two square meters, while corn and rapeseed need 133 and 383 square meters (Singh et al., 2011). So algae production for biofuel may not compete with agricultural land for food and feed consumption. However, algae fuel is still not feasible for commercial production, because it is still in the development process in the laboratory. All of these crops will not be included in this study.

2) The scope of land area in this study is the total agricultural land areas which include all global potentially available land area for agriculture such as cultivated land, grass and woody land, and forested land. However, since grass and woody land and forested land provides a benefit to the environment, this study will exclude all protected grass and woody land and forested land area. Only unprotected grass and woody and forested land areas are taken into account for the total available agricultural land area in this study.

In conclusion, all 12 biofuel crops in this study can be divided into two groups: 1) edible crops, including their residues, such as corn, palm oil, rapeseed, sweet sorghum, soybean, sugar beet and sugarcane, and 2) non-edible biofuel crops, including perennial grasses, such as switchgrass and miscantus, and woody trees, such as silver birch, poplar and willow.

3.2 Equation Model

In the model, the objective function is to maximize energy (GJ) by using crop area (ha) as a decision variable. The maximum energy is the sum of all total energy from each crop type which is calculated by multiplying the crop land area (ha) by the total energy content, including residue for each crop (GJ/ha). There are two main groups: 1) edible crops, such as corn, palm oil, rapeseed, sweet sorghum, soybean, sugar beet, sugarcane, and 2) non-edible crops divided into grasses crop such as switchgrass and miscanthus, as well as woody tree crops such as silver birch, poplar, and willow. The limitation of agricultural area and crop land area that need to be reserved for the food supply of each crop are the constraints. In this case, food supply included food, feed, seed, waste, and other utility. Since the scope of this study is global, there are various land suitabilities and climate zones to account for, therefore the potential land areas are concerned with land suitabilities and climate zones. These different areas are widespread throughout the world. They include not only agricultural land, but also unprotected grass and woody and forestland. The generic model formulation is shown below:

$$\textbf{Max } \mathbf{Z} = \sum (\mathbf{E_i} \times \mathbf{A_i}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where $i = 1, 2, ..., 9$

1 = corn, 2 = palm oil, 3 = rapeseed, 4 = sweet sorghum, 5 = soybean,

6 = sugar beet, 7 = sugarcane, 8 = grasses crop, 9 = woody tree

Z = Energy ($\times 10^6$ GJ)

Ei = Total energy content, including residue (GJ/ha) for each crop i

Ai = Planted Area for each crop i (ha)

S.T.

$\sum$ **Ai** $\leq$ The total amount of agricultural land available in this research area (Mha)

Ai $\geq$ The crop land area needed for crop i to provide adequate food supply (Mha)

Ai $\leq$ The global potential land area for each crop i (Mha)

Viz., $\mathbf{Ai} = \mathbf{Ai}_{\text{Cultivated}} + \mathbf{Ai}_{\text{Grassland}} + \mathbf{Ai}_{\text{Forest}}$

$\sum\mathbf{Ai}_{\text{Cultivated}} \leq$ total cultivated land (Mha)

$\sum\mathbf{Ai}_{\text{Grass/woody}} \leq$ total unprotected grass/woodland (Mha)

$\sum\mathbf{Ai}_{\text{Forest}} \leq$ total unprotected forest land (Mha)

$\sum\mathbf{Ai}_{\text{Cultivated, zone 1}} \leq$ the greatest area for a crop in cultivated land under temperate zone

$\sum\mathbf{Ai}_{\text{Grass/woody, zone 1}} \leq$ the greatest area for a crop in grass and wood land under temperate zone

$\sum\mathbf{Ai}_{\text{Forest, zone 1}} \leq$ the greatest area for a crop in forestland under temperate zone

$\sum\mathbf{Ai}_{\text{Cultivated, zone 2}} \leq$ the greatest area for a crop in cultivated land under tropical zone

$\sum\mathbf{Ai}_{\text{Grass/woody, zone 2}} \leq$ the greatest area for a crop in grass and wood land under tropical zone

$\sum\mathbf{Ai}_{\text{Forest, zone 2}} \leq$ the greatest area for a crop in forestland under tropical zone

$\sum\mathbf{Ai}_{\text{Cultivated,zone 3}} \leq$ the greatest area for a crop in cultivated land under temperate and tropical zone

$\sum \mathbf{Ai}_{\text{Grass/wood,zone 3}} \leq$ the greatest area for a crop in grass and wood land under temperate and tropical zone

$\sum \mathbf{Ai}_{\text{Forest, zone 3}} \leq$ the greatest area for a crop in forestland under temperate and tropical zone

3.2.1 Energy Content

The identification of each crop's energy yield by Miller (2010) was used in this study. The high heating value (HHV) (MJ/kg) of each crop is used to calculate the energy content (GJ/ha). This is done by multiplying the yield (kg/ha) for each crop, which includes crop residue with HHV. The average crop yield is used to calculate the energy content, because of the uncertainty of crop yield. The data for each of the crops were shown Appendix A. For grass crops, the average crop yield for switchgrass and miscanthus is used in the model; same with woody trees, the average yield is used among silver birch, poplar, and willow. That energy contents are shown in Table 3.1.

Table 3.1: Energy content for each biofuel crop

Crop	Average Energy Content with Residue (GJ/ha)	Range
Edible crops		
• Corn	205	126 - 331
• Palm oil	338	253 - 422
• Rapeseed	61	40 - 96
• Sweet Sorghum	165	132- 206
• Soybean	50	36 - 60
• Sugar Beet	522	452 - 572
• Sugarcane	437	333 - 582
Non Edible Crops		
• ***Grasses*** (Switchgrass, Miscanthus)	196	141- 338
• ***Woody trees*** (Silver Birch, Poplar, Willow)	159	114 - 228

Source: Miller, 2010

3.2.2 Total Agricultural Land Area

In general, there are three main areas in the world for harvesting: cultivated land, grass/wood lands, and forested land. The total agricultural land used in this study is the total harvested land area of all crops, such as corn, palm oil, rapeseed, sweet sorghum, soybean, sugar beet, and sugarcane. FAOSTAT (2010) has the total harvesting area for each crop up to 2009.

Grass and woody and forested land have potential for harvesting, however not all these areas can be used. Some of the grass and woody lands and forested land are protected based on the definition of a protected area such as limiting or prohibiting agricultural planting (IUCN and UNEP, 2003).

In this study, only unprotected areas of grass/wood land and forested land are considered. Currently, unprotected grass/wood and forested lands are approximately 3.4 and 2.8 billion hectares, respectively (OPEC Fund for International Development, 2009). Thus, the total available agricultural land area is composed of the total current cultivated land area for selected crops and unprotected grass and woody land and forested land area based on the assumption that unprotected grass and woody and forest land can be converted into cultivated land (Table 3.2). However, in reality, unprotected grass/woody and forest land provide value to the ecosystem, therefore all of them cannot be converted into cultivated land. Thus, the total available agricultural land area will be categorized into five different scenarios that include areas for all current cultivated land area of selected crops with different amounts of unprotected grass and woody land and forest land area (Table 3.2):

First scenario: Baseline model in which the total agricultural land area includes all current cultivated land area of selected crops and unprotected grass and woody lands and forested land area.

Second scenario: The total agricultural land area includes only current cultivated land area of selected crops.

Third scenario: The total agricultural land area includes all current cultivated land area of selected crops and all unprotected grass and woody lands.

Fourth scenario: The total agricultural land area includes all current cultivated land area of selected crops, all unprotected grass and woody lands, and ten percent of unprotected forest land.

Fifth scenario: The total agricultural land area includes all current cultivated land area of selected crops, ten percent of unprotected grass and woody lands, and ten percent of unprotected forest land.

Table 3.2: Total agricultural land available in different scenarios

Crops	**Total Agricultural Land Area (Mha)**				
	1st Scenario	**2nd Scenario**	**3rd Scenario**	**4th Scenario**	**5th Scenario**
All selected crops	375.44	375.44	375.44	375.44	375.44
Unprotected grass/woodland	3,408	0	3,408	3,408	340.8
Unprotected forestland	2,806	0	0	280.6	280.6
Total	6,589.44	375.44	3783.44	4064.04	996.84

3.2.3 Crop Land Area for Food and Feed Consumption

The crop land area for each crop can be calculated by dividing the amount of the total human consumption (tonnes) (FAOSTAT, 2010) by the average crop yield (tonnes/ha) for each crop (Miller, 2010). The total human consumption includes the amount of food for global population, feed for global livestock, seed, waste, and other utilities. These data for each of the crops were shown in Appendix B. The crop land areas for food and feed consumption for each crop in 2009 are shown in Table 3.3

Table 3.3: Land areas for food and feed consumption for each crop in 2009

Crop	Total human and livestock consumption (Million Tonnes)*	Average crop yield (kg/ha)**	Area Need for Food and Feed Consumption (Mha)	Existing Cultivated Land Area* (Mha)
Corn	757.47	8,551	88.58	159.53
Palm oil	43.83	20,000	2.19	14.73
Rapeseed	73.77	2,400	30.74	31.02
Sweet Sorghum	62.39	2,000	31.19	43.74
Soybean	272.89	2,500	109.15	98.83
Sugar beet	253.10	30,000	8.44	4.32
Sugarcane	1,666.87	75,000	22.22	23.27

Source: * FAOSTAT, 2010
** Miller, 2010

Note, the areas need for food and feed consumption from calculation that based on total human and livestock consumption and average crop yield are different from the existing cultivated land area in Table 3.3. This is because the cultivated land area of some crops is used to grow crops for biofuel and these lands may be cultivated more than humans need because of government policy such as subsidies. Also, the amount of calories grown on the field does not equal the amount of calories left for food and feed consumption because of imperfect conversion efficiency. This will make the crop yield less than it should be, thus more land will be needed for cultivation.

3.2.4 Total Potential Land Area

With regards to the total global land area, the availability of harvesting area can be identified with three land use types; cultivated land, unprotected grass and woody lands, and unprotected forested land. The land areas for cultivated land, unprotected grass and woody lands, and unprotected forested land are 1,563; 3,408 and 2,806 Mha, respectively.

When we consider total potential crop land in the specified harvesting area, this can be separated into two main categories, based on weather zone and land suitability. The suitability of land areas for each crop are categorized by cultivated land, unprotected grass/wood lands, and unprotected forested land in Table 3.4 (OPEC Fund for International Development, 2009 and Fischer et al., 2002). However, some crop types are suitable in term of land suitability, but they favor different climate zones. These data were obtained by analyzing global potentials for each of the crops. World maps where each of these crops can be grown are in Appendix C

The climate zone is one of the main factors in crop land allocations; therefore, crop type in this study can be divided into three zones. The first zone is crops that are suitable in temperate weather, such as rapeseed and sugar beet. The second zone is crops that are suitable in tropical weather, such as palm oil and sugarcane. The third zone is crops that can grow in both temperate and tropical weather, such as corn, sweet sorghum, and soybean (OPEC Fund for International Development, 2009 and Fischer et al., 2002). The details are shown in Table 3.4.

For each land use type within each zone, the total value for potential land area should be the greatest numerical areas of all crop types in its zone, because the greatest area includes every different crop area in that zone. For example, the chosen values of group one for cultivated land, unprotected grass and woody lands and unprotected forested land are 735, 328, and 474 Mha, respectively. Similarly in group two, the chosen values for cultivated land, unprotected grass and woody lands and unprotected forested land are 265, 228, and 588 Mha, respectively. For group three, the chosen values for cultivated land, unprotected grass and wood land and unprotected forested land are 966, 859, and 1,179 Mha, respectively.

Table 3.4: Global potential land area for each crop by climate zone and land use type

Climate Zone	Crops	Cultivated Land (Mha)	Unprotected Grass/woody Land (Mha)	Unprotected Forest Land (Mha)	Global Potential Area (Mha)
Zone One Temperate	Rapeseed*	735	328	474	**1,537**
	Sugar beet**	426	204	140	**770**
Limitation Area		**735**	**328**	**474**	
Zone Two Tropical	Palm oil*	83	44	490	**617**
	Sugarcane	265	228	588	**1,081**
Limitation Area		**265**	**228**	**588**	
Zone Three Temperate and Tropical	Corn*	823	577	427	**1,827**
	Sweet sorghum**	750	425	52	**1,227**
	Soybean*	792	682	699	**2,173**
	Grasses and woody trees*	966	859	1,179	**3,004**
Limitation Area		**966**	**859**	**1,179**	
Total Limitation Area		**1,563**	**3,408**	**2,806**	

Source: * OPEC Fund for International Development, 2009
** Fischer et al., 2002

3.3 Forecasted Crop Land Proportions through 2050

Since the global population is increasing continuously every year, it causes increasing food demand that correlates to the crop land areas for food and feed. So, in the future, the land area requirement for food and feed may be increase, which affects the crop land area for biofuel production. This section tries to predict the trend of optimum for biofuel land allocation and maximum energy production through 2050. The amount of crop land area for food is the point of this prediction. These areas can be calculated by dividing the amount of food demand by crop yield per area. However, the food demand and crop yield needs to be forecasted with an increasing annual rate. FAO (2006) reports the increase in the rate of demand for food separated by crop types, such as cereals, vegetable oil, sugar crop and feed product. The increase in the annual rate of food demand for all crop types tends to decrease from 2001 to 2050 (FAO, 2006) (Table 3.5). That is the same as results with the rate for crop yield (Tweeten and Thompson, 2008) (Table 3.5). The annual trends of food demand and crop yield for each crop are shown in Figure 3.3 and 3.4, respectively.

Table 3.5: Annual rate of increasing for food and feed demand and crop yield by crop type

Crop	Annual food demand increasing rate (percentage)**		Annual increase crop yield rate (percentage)*		
	2001-2030	2030-2050	2000-2024	2025-2049	2050
Cereals	1.2	0.6	1.41	1.04	0.83
Vegetable oil	2.3	1.6	0.48	0.43	0.39
Sugar crop	1.3	0.7	0.93	0.76	0.64
Feed	1.6	0.8			

Source: * Tweeten and Thompson, 2008
** FAO, 2006

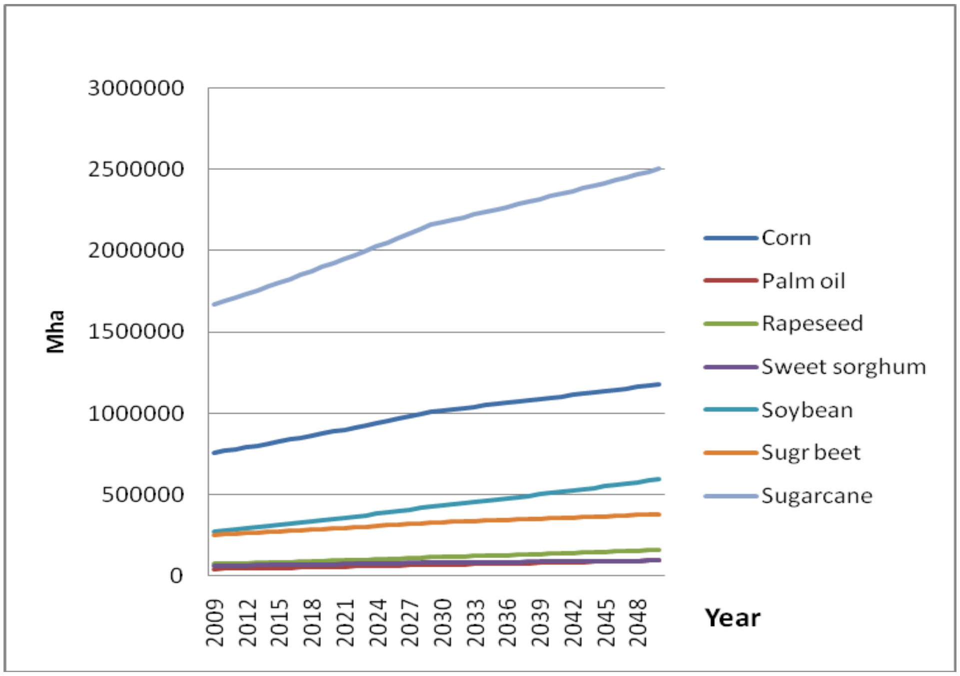

Figure 3.4: Annual trends of food demand for selected crops through 2050

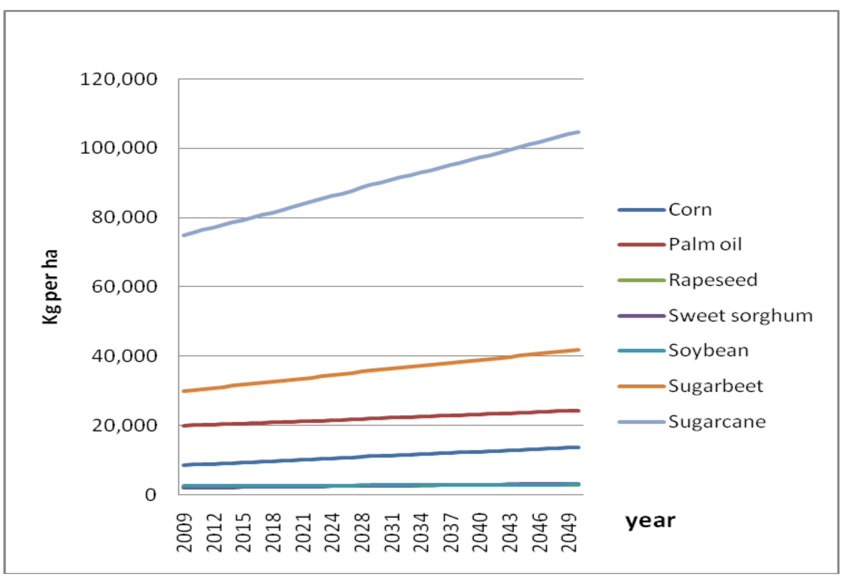

Figure 3.5: Annual trends of crop yield for selected crops through 2050

Moreover, when annual crop yield changes, it affects the energy content that is related to HHV and crop yield. Thus, we need to use the energy content that is forecasted through 2050 for calculation in this section. The annual trend of energy content is shown in Figure 3.5

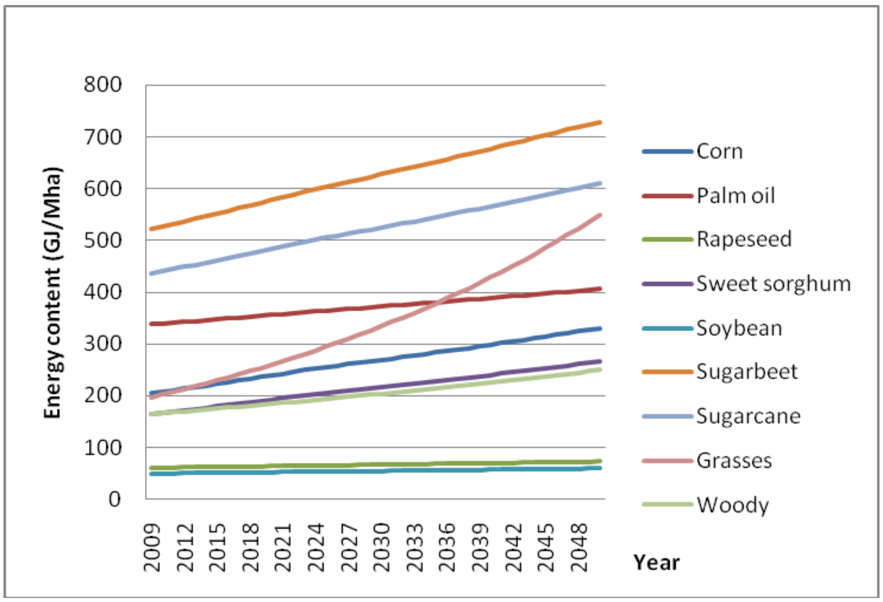

Figure 3.6: Annual trends of energy content for each crop through 2050

Thus, the equation model is calculated based on the forecasting value from 2010 to 2050 for energy content, total agricultural land area, and area for food and feed consumption.

3.4 Sensitivity Analysis

Sensitivity analysis is a method to study how sensitive or uncertain the equation model is to change in the value of the parameters in the model. It shows the effect of the changes in the result of the model. This technique allows explanation of the relationship between input and output variables in the model and is useful for policy makers for decision making (Saltelli et al., 2008; Breierova and Choudhari, 2001). In this research, the sensitivity of the objective function to the variation of energy content, the amount of area for food and feed, and the total potential land area for each crop type in the constraint are tested.

3.4.1 Objective Function Sensitivity Analysis

Naturally, the uncertainty of crop yield depends on many factors, such as weather, soil quality, water resource, etc. In this study, the energy content is related to the crop yield, so variability of energy content will occur, which change affects the result of the equation. The extent of variability in energy content can be seen as an increase or decrease from the average crop yield based on minimum or maximum of crop yield. For this analysis, there are three changes in the value of energy content for each crop. This is done while fixing the others at their average values. The interested value will be set at the maximum, average and minimum of energy content.

3.4.2 Constraint Sensitivity Analysis

Crop land area for consumption and potential crop land area, that are the constraints, can be changed continuously. Population growth is the main factor that alters the crop land area for consumption, while changing natural systems, such as weather, soil quality, water, etc. causes a change in potential crop land. Therefore, this variability will affect the result of the assumption. For crop land area for consumption, the range of variability for constraint sensitivity analysis will be increased or decreased based on the uncertainty of the crop yield. The amount of land area for food and feed consumption for each crop type will be set at maximum and minimum values, while fixing the others at their average values. Similar to potential crop land area, the amount of land area for each crop will increase and decrease by 25 percent of current potential land area, while fixing the others at their current amount.

3.4 Structure of Equation Model

Linear programming that used in the equation model follow equation model (1) as described in topic 3.2 and the data which are energy content, total agricultural land area, crop land area for food and feed consumption, and total potential land area are put into this model. The structure of model with data is as follows.

3.4.1 Objective function

The maximum energy production which is the objective function is calculated by multiplying average energy content by land area for each crop. In this model, average energy content (GJ/Mha)is the coefficients as described in Table 3.1 and the land area is a decision variable.

$$\text{MAX } Z = 205\, A_{\text{Corn}} + 338\, A_{\text{Palm oil}} + 61\, A_{\text{Rapeseed}} + 165\, A_{\text{Sweet sorghum}} + 50\, A_{\text{Soybean}}$$
$$+ 522\, A_{\text{Sugar beet}} + 437\, A_{\text{Sugar cane}} + 196\, A_{\text{grass}} + 159\, A_{\text{woody}}$$

3.4.2 Constraints

There are three constraints in this model; total cultivated land area, crop land area for food and feed consumption and total potential land area described as follows.

3.4.2.1 Total Agricultural Land Area

Total agricultural land areas are composed of the total current harvesting area for all selected edible biofuel crop, unprotected grass and woody land, and unprotected forest land as described in the first scenario in Table 3.2. The total land area of selected crop will not be greater than the total agricultural land area, 6589.44 Mha, as shown in the following equation.

$A_{Corn} + A_{Palm\ oil} + A_{Rapeseed} + A_{Sweet\ sorghum} + A_{Soybean} + A_{Sugar\ beet} + A_{Sugar\ cane} + A_{grass} + A_{woody} \leq 6589.44$

3.4.2.2 Crop Land Area for Food and Feed Consumption and Potential land area for each Crop

Crop land area for food and feed consumption is calculated by dividing the amount of total food and feed consumption by the average crop yield for each crop as described in Table 3.3. The potential land area for each crop is from secondary data as shown in Table 3.4. Land areas for each crop have to be greater than its land area for food and feed consumption and have not to be greater that the potential land area for each crop as shown in the following equation.

$$88.58 \leq A_{Corn} \leq 1827$$

$$2.19 \leq A_{Palm\ oil} \leq 617$$

$$30.74 \leq A_{Rapeseed} \leq 1537$$

$$31.19 \leq A_{Sweet\ sorghum} \leq 1227$$

$$109.15 \leq A_{Soybean} \leq 2173$$

$$8.44 \leq A_{Sugar\ beet} \leq 770$$

$$22.22 \leq A_{Sugar\ cane} \leq 1081$$

$$A_{grass} + A_{woody} \leq 3004$$

3.4.2.3 Harvested land area

The global harvested land areas are composed of three land use types; cultivated land (C), unprotected grass and wood lands (G), and unprotected forest land (F) as described in total limitation area in Table 3.4. The total area of selected crops will not be greater than the global harvested land area in each land use type as shown in the following equation.

$$A_{Corn,C} + A_{Palm\ oil,C} + A_{Rapeseed,C} + A_{Sorghum,C} + A_{Soybean,C} + A_{Sugar\ beet,C} + A_{Sugar\ cane,C} + A_{grass,C} + A_{woody,C} \leq 1563$$

$$A_{Corn,G} + A_{Palm\ oil,G} + A_{Rapeseed,G} + A_{Sorghum,G} + A_{Soybean,G} + A_{Sugar\ beet,G} + A_{Sugar\ cane,G} + A_{grass,C} + A_{woody,C} \leq 3408$$

$$A_{Corn,F} + A_{Palm\ oil,F} + A_{Rapeseed,F} + A_{Sorghum,F} + A_{Soybean,F} + A_{Sugar\ beet,F} + A_{Sugar\ cane,F} + A_{grass,C} + A_{woody,C} \leq 2806$$

Viz., $A_{Corn} = A_{Corn,C} + A_{Corn,G} + A_{Corn,F}$

$$A_{Palm\ oil} = A_{Palm\ oil,C} + A_{Palm\ oil,G} + A_{Palm\ oil,F}$$

$$A_{Rapeseed} = A_{Rapeseed,C} + A_{Rapeseed,G} + A_{Rapeseed,F}$$

$$A_{Sweet\ sorghum} = A_{Sweet\ sorghum,C} + A_{Sweet\ sorghum,G} + A_{Sweet\ sorghum,F}$$

$$A_{Soybean} = A_{Soybean,C} + A_{Soybean,G} + A_{Soybean,F}$$

$$A_{Sugar\ beet} = A_{Sugar\ beet,C} + A_{Sugar\ beet,G} + A_{Sugar\ beet,F}$$

$$A_{Sugar\ cane} = A_{Sugar\ cane,C} + A_{Sugar\ cane,G} + A_{Sugar\ cane,F}$$

$$A_{grass} = A_{grass,C} + A_{grass,G} + A_{grass,F}$$

$$A_{swood} = A_{wood,C} + A_{wood,G} + A_{wood,F}$$

3.4.2.4 Total potential land area

Potential land area for each crop is based on land suitability and climate zone that can be divided into three zones; temperate, tropical and mixed zone between temperate and tropical. Also, each zone is divided into cultivated land (C), unprotected grass and wood lands (G), and unprotected forest land (F). For each land use type within each zone, the land areas have not to be greater than the greatest value of the land area of crop in its group as described in topic 3.2.4 and Table 3.4. The equation is shown below.

Zone 1: temperate zone (rapeseed and sugar beet)

For cultivated land: $A_{\text{Rapeseed,C}} + A_{\text{Sugar beet,C}} \leq 735$

For unprotected grass and woody land: $A_{\text{Rapeseed,G}} + A_{\text{Sugar beet,G}} \leq 328$

For unprotected forested land: $A_{\text{Rapeseed,F}} + A_{\text{Sugar beet,F}} \leq 474$

Zone 2: tropical zone (palm oil and sugarcane)

For cultivated land: $A_{\text{Palm oil,C}} + A_{\text{Sugar cane,C}} \leq 265$

For unprotected grass and woody land: $A_{\text{Palm oil,G}} + A_{\text{Sugar cane,G}} \leq 228$

For unprotected forested land: $A_{\text{Palm oil,F}} + A_{\text{Sugar cane,F}} \leq 588$

Zone 3: mixed zone between temperate and tropical (corn, sweet, sorghum, soybean, and non-edible crop (grasses and woody trees)).

For cultivated land: $A_{\text{Corn,C}} + A_{\text{Sweet sorghum,C}} + A_{\text{Soybean,C}}$

$+ A_{\text{Non-edible,C}} \leq 966$

For unprotected grass and woody land: $A_{\text{Corn,G}} + A_{\text{Sweet sorghum,G}} + A_{\text{Soybean,G}}$

$+ A_{\text{Non-edible,G}} \leq 859$

For unprotected forested land: $A_{\text{Corn,F}} + A_{\text{Sweet sorghum,F}} + A_{\text{Soybean,F}}$

$+ A_{\text{Non-edible,F}} \leq 1179$

The model will determine the maximum energy production and the optimum land area without affecting food and feed consumption.

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CHAPTER FOUR

RESULT AND DISCUSSION

The optimization approach by linear programming is used in this study to find the maximum biofuel energy production with food consumption focusing on edible crops such as corn, palm oil, rapeseed, sweet sorghum, soybean, sugar beet, and sugarcane, as well as non-edible crops such as switch grass, and miscanthus. The study found the upper limit of biofuel production which can be obtained from the crop system. The results consist of energy production based on the optimum land area for selected crops with the assumption that unprotected grass and woody land and forest land can be converted into cultivated land for biofuel crops. To make the results more realistic, the value of the ecosystem will be considered in different scenarios. The forecast for energy production and optimum area in the future are also considered. Also sensitivity analysis is used to calculate how energy content, crop land area for food and feed consumption, and potential land area affect this result.

4.1 Result of the global maximum biofuel production potential (First scenario)

The maximum energy production obtained from the model is 1,484.65 EJ, derived from the optimum area for all selected crops of 5,219 Mha. For edible crops, corn has the largest area, 35.0 percent of the optimum area, while sugarcane, sugar beet, and rapeseed make up 20.67, 14.75, and 6.97 percent of the optimum area, respectively.

The contribution of non-edible crops is only from grasses, with 19.86 percent of the optimum area. When considering the relative proportion between edible and non-edible crops, 80 and 20 percent of the optimum area is made up of edible crops and non-edible crops, respectively (Table 4.1). Note that there is no amount of land area for woody trees because the model contributes the land area based on energy content. The energy content of woody trees is lower than some crops, although it is higher than others. This is because the optimal land areas are due to the constraints that control the lower limit of the amount of land area, while there is no constraint for woody trees.

Table 4.1: Energy production and optimum area for food and feed consumption and biofuel

Crops	Optimum area (Mha)	Area for food/feed consumption (Mha)	Energy Production for consumption (EJ)	Area for biofuel (Mha)	Energy Production for biofuel (EJ)
1. Edible Crops					
1.1 Corn	1,827.00	88.58	12.31	1,738.42	362.22
1.2 Palm oil	2.19	2.19	0.74	0	0
1.3 Rapeseed	364.00	30.74	1.88	333.26	20.33
1.4 Sweet Sorghum	31.19	31.19	0.99	0	4.15
1.5 Soybean	109.15	109.15	5.46	0	0
1.6 Sugar Beet	770	8.44	4.41	761.56	397.53
1.7 Sugarcane	1,078.81	22.22	6.67	1,056.59	464.77
2. Non-edible Crops					
2.1 Grasses	1,036.66	-	-	1,036.66	203.19
2.2 Woody	0	-	-	0	0
Total	**5219**	**292.51**	**32.46**	**4,926.49**	**1,452.19**
Total Energy production (EJ)	**1,484.65**				

The maximum energy production is comprised of two categories: energy production for food and feed consumption and energy production for biofuel. The production of energy comes from different crop types and different amounts of land area. The production of food energy is derived from all seven selected crops: corn, palm oil, rapeseed, sweet sorghum, soybean, sugar beet, and sugarcane; this total is approximately 32.46 EJ. The total crop land area for food and feed consumption is 292.51 Mha, which is about 6 percent of the total area for both food and feed consumption and biofuel. With respect to the production of biofuel energy, it comes from six selected crops: corn, rapeseed, sweet sorghum, sugar beet, sugarcane, and grasses; this total is 1,452.19 EJ. The total crop land area for biofuel production is 4,926.49 Mha, which is about 94 percent of the total area for both food and feed consumption and biofuel (Table 4.1).

Since energy content used in the model includes energy produced by crop residue, the total energy production from the model is composed of energy from both food and feed consumption and biofuel as well as the residue. When considering energy production for food and feed consumption, energy from the residue needs to be subtracted from the total energy production before calculation, because in reality humans cannot consume crop residue. Note that no amount of land area is contributed by sweet sorghum for biofuel energy production, but it creates 4.15 EJ of energy which is the energy from its residue. Similar to sweet sorghum, the biofuel energy production from corn and sugarcane also includes their crop residue remaining after food and feed consumption.

When considering the area allocation for biofuel production, there are five crop types that compose the 4926.49 Mha of biofuel land area. The largest proportion of area is corn, with 35 percent, while rapeseed is the smallest, with 7 percent (Figure 4.1). The total optimum land area for biofuel energy production contributes 1,452.19 EJ. This energy production can be grouped by biofuel type into two groups: ethanol and biodiesel. The ethanol group consists of corn, sweet sorghum, sugar beet and sugarcane, while only rapeseed is a feedstock for biodiesel. About 99 percent of total biofuel energy production is for ethanol. Since the efficiency of energy production from biofuel crops for consumption is not perfect, there are some energy losses. In reality, the total net energy production for biofuel needs to account for energy conversion efficiency. The result is net energy production of 520.5 EJ; ethanol and biodiesel create approximately 514.6 and 5.9 EJ, respectively (Table 4.2). This total net biofuel energy production can be converted to a volume in gallons, whereby 1 EJ equals the energy contained in 7,589.56 million gallons (US) of automotive gasoline. The total net biofuel energy production is then 3,905,585.91 and 44,778.38 million gallons for ethanol and biodiesel, respectively (Table 4.3).

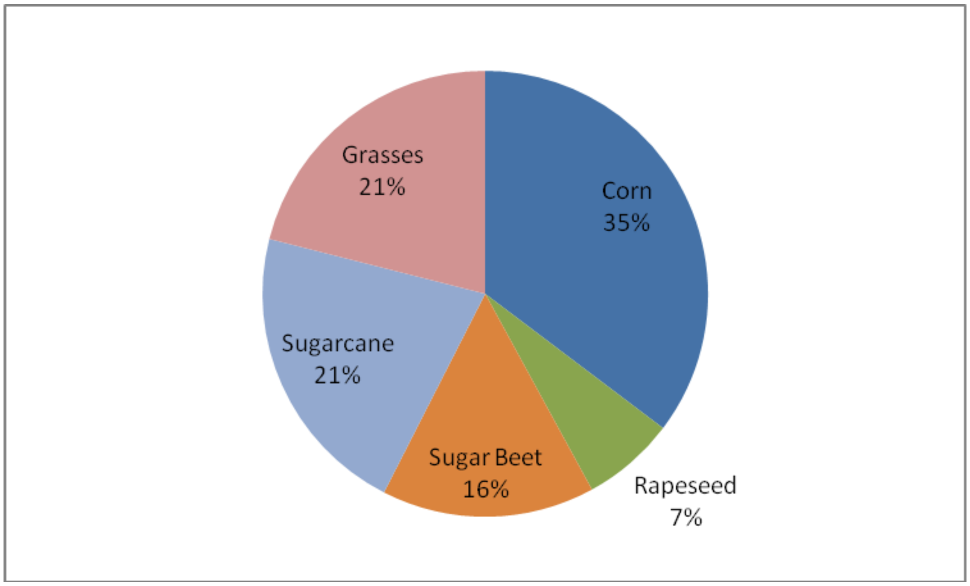

Figure 4.1: Proportion of the optimum area for biofuel production of selected Crops

Table 4.2: Net energy production and energy conversion efficiency

Crops	Biofuel Energy Production (EJ)	Conversion Efficiency	Net Energy Production (EJ)
Ethanol Crops			
Corn	362.22	0.55	199.22
Sweet sorghum (residue)	4.15	0.40	1.66
Sugar beet	397.53	0.12	47.70
Sugarcane	464.77	0.38	176.61
Non-edible crop (grasses)	203.19	0.44	89.40
Total	1431.86		514.60
Biodiesel Crop			
Rapeseed	20.33	0.29	5.90

Source: Department for Transportation, UK, 2006

Table 4.3: Biofuel energy production for ethanol and biodiesel

Biofuel types	Crop types	Total Energy production (EJ)	Converting to Gallon Unit (Million Gallons)	Biofuel production in 2009* (Million Gallons)	Crop land area Mha.	Energy production per Area (EJ/Mha)
Ethanol	Corn, Sweet sorghum (residue), Sugar beet, Sugarcane, and Non-edible crops	514.6	3,905,585.91	19,227	4,593.23	0.11
Biodiesel	Rapeseed	5.9	44,778.38	3,926	333.26	0.02
Total		520.5	4,026,259.86	23,153	4926.49	0.12

Source: * Earth Policy Institute, 2010

The results in this study illustrate the maximum production potential of biofuel energy, which can be obtained from the crop system based on the assumption that all unprotected grass and woody and forest lands can be converted into cultivated land. The maximum biofuel energy production and the total optimum crop land area are large values when comparing them with the global energy demand and global agricultural land in 2009. However, the result in terms of biofuel energy production per area, based on the maximum energy production and total optimum land area for biofuel, is 0.12 EJ/Mha, which can be useful in comparing the potential land area in terms of biofuel energy production (Table 4.3).

The potential biofuel energy production per area of land, 0.12 EJ/Mha, can be used to calculate the land area requirement for biofuel production based on a target biofuel production. When comparing the land area requirement of this study to the studies of IEA (2006) and Ravindranath et al. (2009) – contained within UNEP (2009), they consider the data from the different studies about land area requirements following their biofuel production targets – this study provides a similar land area requirement for biofuel. The total crop area for biofuel in this study is 4,920.49 Mha, which conforms to Nonhebel's (2005) study that study applies the footprint concept to calculate the biomass crop land area. His results show that the global land requirement for biomass crops, based on the population in 2010 has a range of 511.93 – 13,433.25 Mha, which varies with agricultural practices (Table 4.4).

Table 4.4: Comparing the land area for biofuel between the calculation in this study and other studies

Studies	**Biofuel target**	**Energy Production (EJ)**	**Land Area Need (Mha)**	**Land Area Needed by calculation in this study (Mha)**
IEA (2006)	In 2030, 3 percent of energy for transportation	3.9	34.5	32.5
Ravindranath et al. (2009)	10 percent of energy for gasoline and diesel requirement	14.2	118 - 508	118.3
Nonhebel (2005)	Global potential		511.93-13,433.25	4,920.49

Source: UNEP, 2009

Only a proportion of the optimum area of corn, rapeseed, sugar beet, sugarcane and grasses contributes to grow biofuel. When considering biofuel types, rapeseed is the only crop in this model that should be grown for biodiesel, while corn, sugar beet, sugarcane and non-edible crops are grown for ethanol. The result correlates to actual global ethanol production, where about 90 percent of global ethanol production comes from corn, sugarcane, and sugar beet. Also biodiesel production follows the same trend as global production of biodiesel, where almost 60 percent comes from rapeseed.

Note that in reality soybean and palm oil are currently grown for biodiesel production and make up about 25 percent of global biodiesel production. This is because rapeseed can be grown only in temperate weather zones, while the demand for biodiesel production exists in the tropical zones. Soybean and palm oil are potential feedstocks for biodiesel in these tropical zones. Many countries in Southeast Asia have policies that support biodiesel from palm oil because it has high energy content and it is easy to cultivate in this area (Sumathi et al., 2008). In addition, this model also considers the potential land area based on climate zones, grouped by temperate, tropical and a mix of temperate and tropical. Palm oil is in the tropical zone, along with sugarcane, while soybeans are in the mix of temperate and tropical, along with corn, sweet sorghum, and non-edible crops. However, palm oil and soybeans have less energy content than the rest of the crops in their group, so the optimum land area of palm oil and soybeans is not included in the model see Table 3.1 and 3.4

When comparing the global cultivated land area, about 1563 Mha, (OPEC Fund for International Development, 2009) to the total optimum crop land area for biofuel, 4,920.49 Mha, this study's results exceed the global cultivated land by approximately three times. This value seems to be the theoretical value for the potential global land area for biofuel, based on the assumption that unprotected grass and woody land and forest lands are converted into cultivated land. However, in reality, there are many factors that determine how land area should be allocated and which biofuel crop types are appropriate for biofuel production.

The maximum biofuel energy production, the total amount of optimum crop land for biofuel production, as well as the proportion of land area for the selected biofuel crops demonstrate the global potential of biofuel in terms of land use. The biofuel energy production per area of land that is calculated in this study is the optimal global biofuel production.

4.2 Results of different scenarios

Since the assumption in this study is that all unprotected grass and woody land and forest land can be converted into cultivated land, the result seems infeasible in reality. A more reasonable approach is to consider the five different scenarios, based on the feasibility of the agricultural land area available for planting, which is concerned the value of the ecosystem for unprotected grass and woody and forest lands. The result from each scenario is shown in Table 4.4.

Table 4.5: Biofuel energy production, total optimum crop land area and crop types in different scenarios

	1st Scenario **100% of unprotected forest and grass/wood**	**2nd Scenario** **None of unprotected forest and grass/wood**	**3rd Scenario** **No unprotected forest, 100% grass/wood**	**4th Scenario** **10% unprotected forest, 100% grass/wood**	**5th Scenario** **10% unprotected forest, and 10% grass/woody**
Energy Production for Biofuel (EJ)	520.5	11.80	295.28	322.2	76.29
Total Optimum Crop Land Area (Mha)	4,926.49	82.93	2,685.49	2,909.59	704.33
Crop Types for Biofuel	Corn, rapeseed, sugar beet, sugarcane, and grasses	Sugarbeet	Corn, sugarbeet, sugarcane, and grass	Corn, rapeseed, sugarbeet, sugarcane, and grass	Sugar beet and sugarcane

The U.S. Energy Information Administration (2010) reports that world energy consumption in 2009 was approximately 509 EJ. Approximately 20 percent of this consumption, 100.05 EJ, was used in the transportation sector. Comparing the results of different scenarios, the maximum possible biofuel production (first scenario) is 520.5 EJ with 4,926.49 Mha for the total optimum land area; this can serve all global energy demand, which is about five times the energy demand for the transportation sector (Table 4.3). This result does not seem reasonable because the land area needed for this scenario exceeds the global cultivated land area, which means that the land area of other crops has to be converted to grow the selected biofuel crops. Also, the plentiful, unprotected grass or woody and forest land areas need to be converted into cultivated land (Figure 4.2). However, scenario one illustrates the possible global land area for biofuel crops. For the other scenarios, the value of biodiversity and the ecosystem for the unprotected grass and woody and forest lands is considered. So, in reality, these land areas cannot be converted into cultivated land without affecting biodiversity.

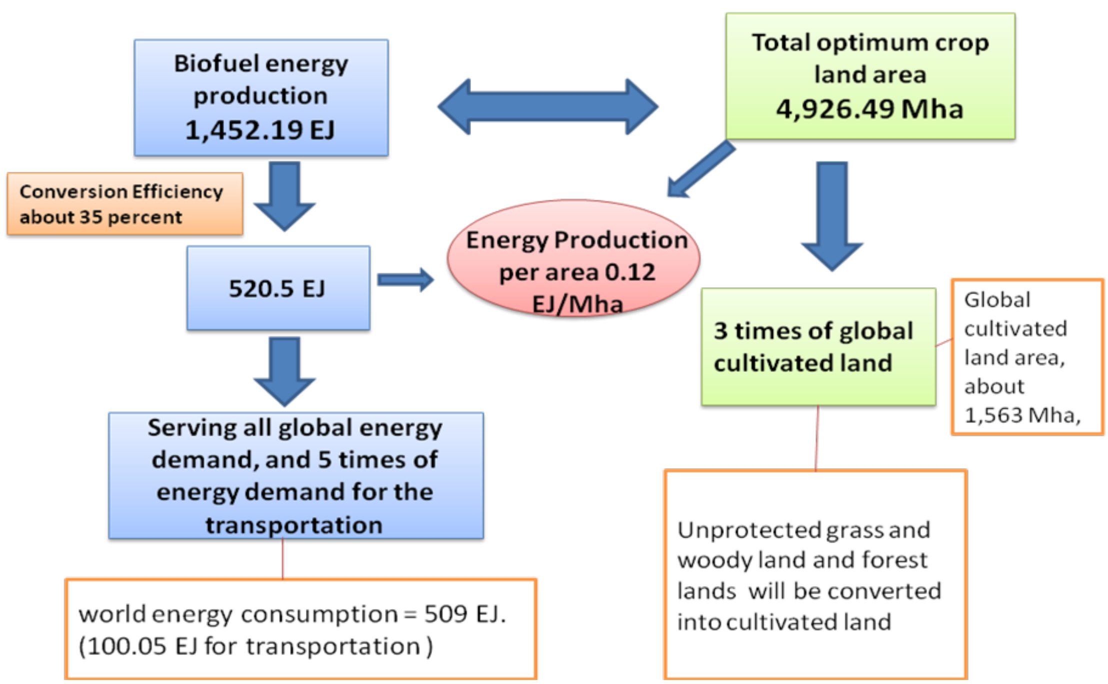

Figure 4.2: Maximum potential energy and the total optimum land area

When considering all scenarios, the fifth scenario appears to be realistically possible because the degree of the invasion of grass and woody and forest land areas is not more than 10 percent. The energy production for biofuel obtained in this scenario is 76.29 EJ. This amount can serve about 72 percent of energy demand for transportation, while current biofuel production is only about 3 percent for transportation sector **(**Earth Policy Institute, 2010 and U.S. Energy Information Administration, 2010). From this biofuel energy production, the total optimum land area is 704.33 Mha, which is about 45 percent of the global cultivated land area. This percentage is similar to the Wolf et al. (2003) study that illustrates that about 45 percent of global crop land area contributes to biofuel production, based on good agricultural practices in 2050.

For the proportion of optimum area for the selected crops in the fifth scenario, which considers the value of biodiversity and the ecosystem, there are two crop types contributing to biofuel: sugar beet and sugarcane. These are different from the first scenario. Because of the limitation placed on total cultivated land area of 10 percent of unprotected grass and woody land and forest land area, the model will focus on the crops that have maximum energy content. In this case, sugar beet and sugarcane are the top two crop types with maximum energy content. The more limitations to available cultivated land area, the less diversity of crop type proportions.

4. 3 Forecasting Energy Production and Crop Land Area through 2050

When forecasting through 2050, the value of the relation factors in this model needs to be changed. The population growth is the main factor that directly affects the global demand for food and feed consumption. In addition, agricultural technology is developed continuously, increasing the crop yield. This increase will affect the crop land area for food and feed consumption. Figure 3.5 shows the annual trend of area for food and feed consumption of selected crops through 2050. In most crops the trend of this area seems to be stable because the demand for food and feed, when correlated to crop yield, also change in the same direction. However, rapeseed and soybean increase continuously and the increasing crop yield is not enough to match the increase in food demand. In these cases, additional crop land area is needed to serve the increased demand (Table 3.5). Also, the increase of crop yield makes energy content increase.

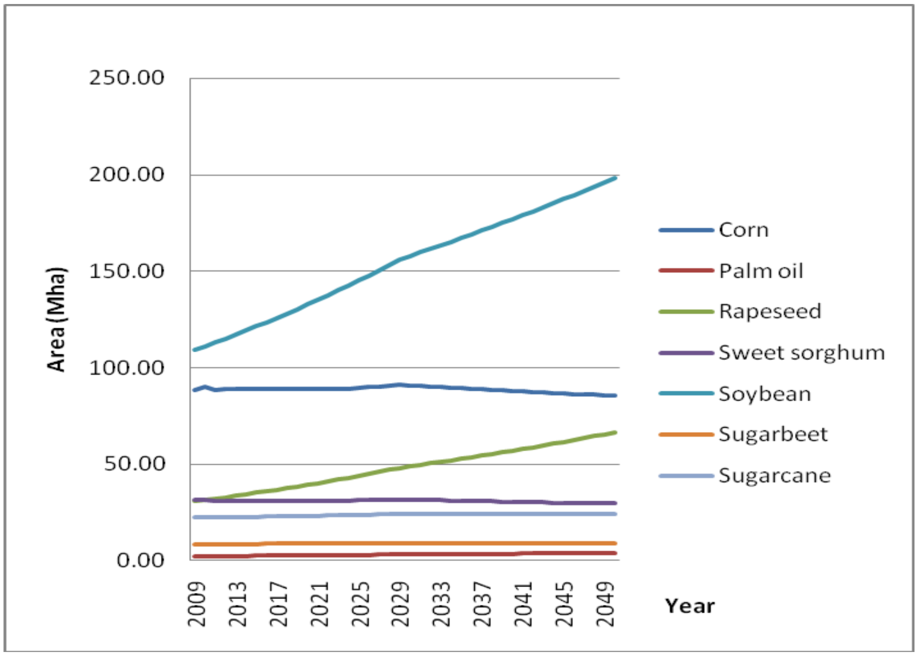

Figure 4.3: Annual trends of area for consumption for selected crops through 2050

Using predicted data through 2050, both energy content and area for food and feed consumption are forecasted and then used for calculation in the equation model. The results show that the maximum energy production tends to increase until 2050 (see Figure 4.3), while the total optimum land area tends to be stable. Therefore, the biofuel energy production per area of land, in 2050, will be 0.21 EJ/Mha, which is higher than it is in 2009. However, the proportion of land area for each crop changes. The optimum land area for palm oil, sweet sorghum and soybean, which do not contribute to biofuel, will change in relation to the variability in their consumption demand. The selected crops for biofuel production, which are rapeseed and sugar beet, do not change. Corn tends to decrease while grasses tend to increase until 2020; they then stabilize (Figure 4.4) because the energy content of grasses increases until it is higher than the energy content of corn in 2020 (Figure 3.5).

This result seems unexpected. Since the annual global population will increase continuously, the food demand in the future should be correlated to the increase in population growth. Therefore, this should affect crop land area for human consumption. However, agricultural technologies also develop, so the annual crop yields tend to increase continuously. The smaller crop land area used in the future may be used to harvest more agricultural products than the lager crop land area in the present. Thus, the trend of land area for human consumption through 2050 does not change as much. On the other hand, energy production tends to increase, due to the increase in crop yield.

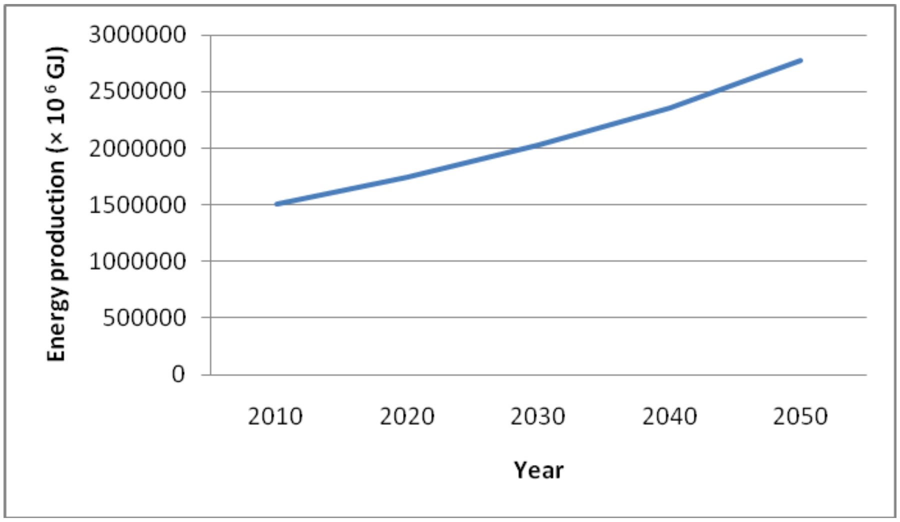

Figure 4.4: Maximum energy productions through 2050

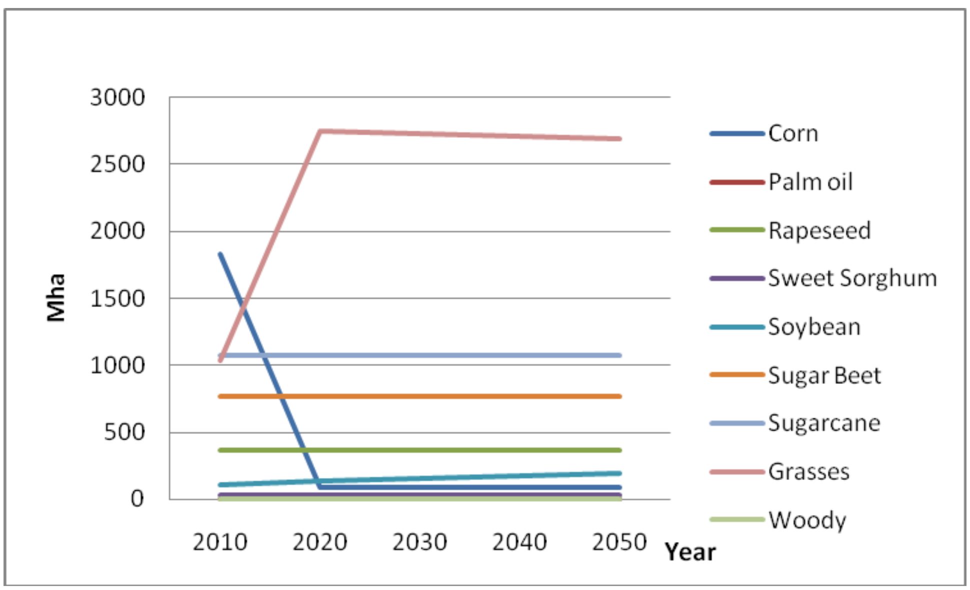

Figure 4.5: The optimum crop land areas for selected crops through 2050

4.4 Sensitivity Analysis

Because of the variability in energy content, land area for human consumption, and potential crop land area, results may be affected. To deal with these uncertainties, sensitivity analysis is conducted by varying the energy content in the objective function and by varying the land area for human consumption and potential crop land area in this model.

4.4.1 Objective Function Sensitivity

The changing of energy content, which is the parameter of the objective function, will affect the results. Objective function sensitivity analysis will show how sensitive the results are to changes in the energy content for selected crop types. The results are shown in the bar chart in Figure 4.4. The middle column shows the average energy content and the other two columns represent two possible energy contents, based on minimum and maximum crop production. The maximum energy production is calculated by fixing all the energy contents with their average values while changing the energy content of the target crop type. The results illustrate that the land area for palm oil, rapeseed, soybean, and sugar beet are not sensitive to energy content. The land area of corn and sugarcane will decrease when the energy content is changed to a minimum. These cases make the area of grasses and palm oil increase from 1,036.66 to 2,775.069 Mha and 2.19 to 464 Mha, respectively. Sweet sorghum, grasses, and woody tree are sensitive to maximum energy content. This change makes the land area of corn decrease from 1,827 to 1,667.849 and 1,827 to 88.5 Mha, for sweet sorghum and grasses, respectively, while area for corn and grasses decrease from 1,827 to 88.5 and 1934.92 to 0 Mha in case of woody trees (Figure 4.5).

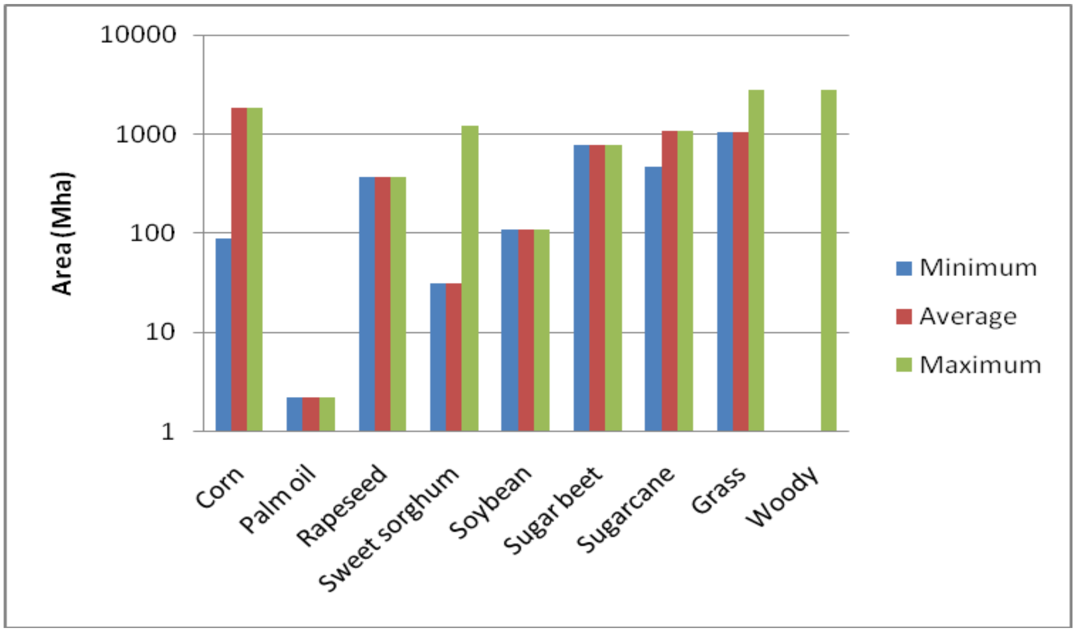

Figure 4.6: Summary of the sensitivity of the optimum land area for selected crop types to energy content

The improvement of agricultural practices that increase energy yield per area will affect the land area requirements. The results from the objective function sensitivity analysis show that if the yield of sweet sorghum, grasses and woody tree is improved, then farmers will be interested in growing them.

4.4.2 Constraint Sensitivity

The uncertainty of cropland area needed for food and feed consumption and global potential crop land area, which are constraints in the model, will affect the results. Constraint sensitivity analysis will show how sensitive the results are to the variability of cropland area for human consumption.

4.4.2.1 Change of Crop Land Area for Food and Feed Consumption

This analysis illustrates the sensitivity of the optimum land area of selected crop types to crop land area for human consumption. Figure 4.6 is similar to the bar chart in the objective function sensitivity analysis. The maximum energy production is calculated from the average and current value by varying the land area for human consumption of the target crop type, fixing the remainder as their average value. The results show that corn, rapeseed, sugar beet, sugarcane, grasses, and woody trees are not sensitive to crop land area for food and feed consumption. Palm oil, sweet sorghum, and soybean are sensitive to the change in crop land area for food and feed consumption. These crops land areas change in line with the change in crop land for food and feed consumption. In these cases, the optimum area for grasses is summed, except palm oil, which does not affect any other crops.

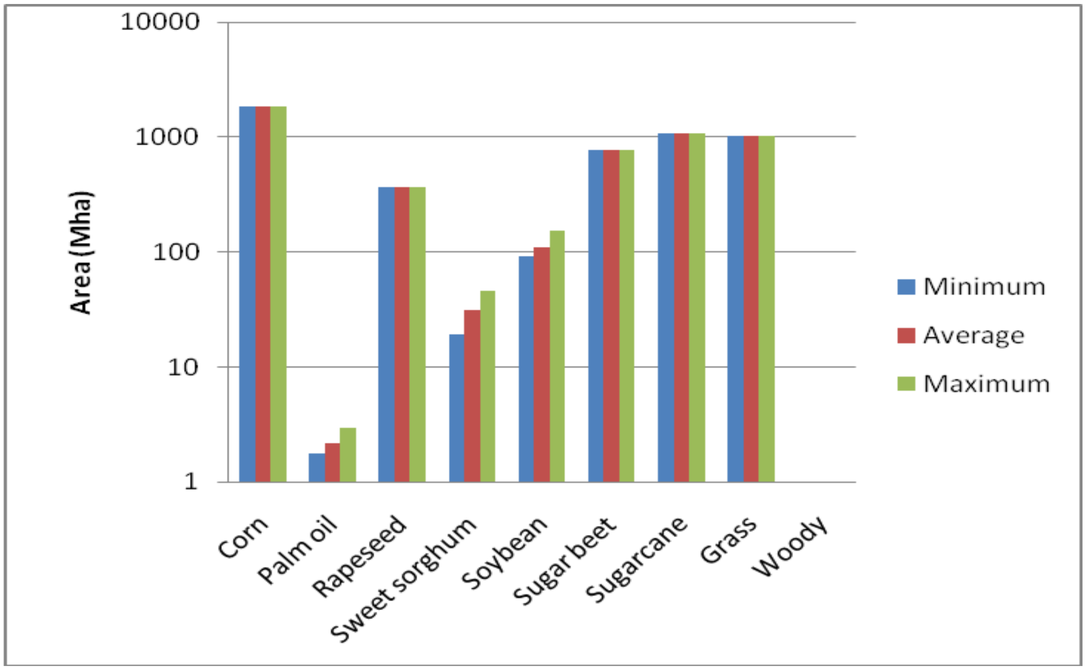

Figure 4.7: Summary of the sensitivity of the optimum land area for selected crop types to land area for food and feed consumption

From the results of constraint sensitivity analysis for crop land area for food and feed consumption, grasses will play an important role for biofuel production when consumption demand increases. Moreover, the increase in grasses will not create a problem with clearing unprotected forested land.

4.4.2.2 Change in Potential Crop Land Area

This analysis illustrates the sensitivity of the optimum land area for selected crop types to a 25 percent increase or decrease in the potential crop land area. Figure 4.7 is similar to the bar chart in the objective function sensitivity analysis. The maximum energy production was calculated from the average and current value by varying the potential land area for each crop type, while fixing the remainder as the average value. The results show that the optimum land area of palm oil, rapeseed, sweet sorghum, soybean, grasses and woody is not sensitive to potential crop land area. Corn and sugar beet land areas change in the same direction with the change in potential crop land area. In the case of corn sensitivity, grasses increase from 1,036.66 to 1,493.4 with a 25 percent decrease in potential corn area, while sugarcane decreases from 1,078.81 to 579.90 Mha with a 25 percent increase in potential sugar beet area. For sugarcane, it is sensitive in the same direction with a 25 percent decrease in potential sugarcane area but remains stable with a 25 percent increase. This case makes the optimum area of palm oil increase from 2.19 to 270.25 Mha.

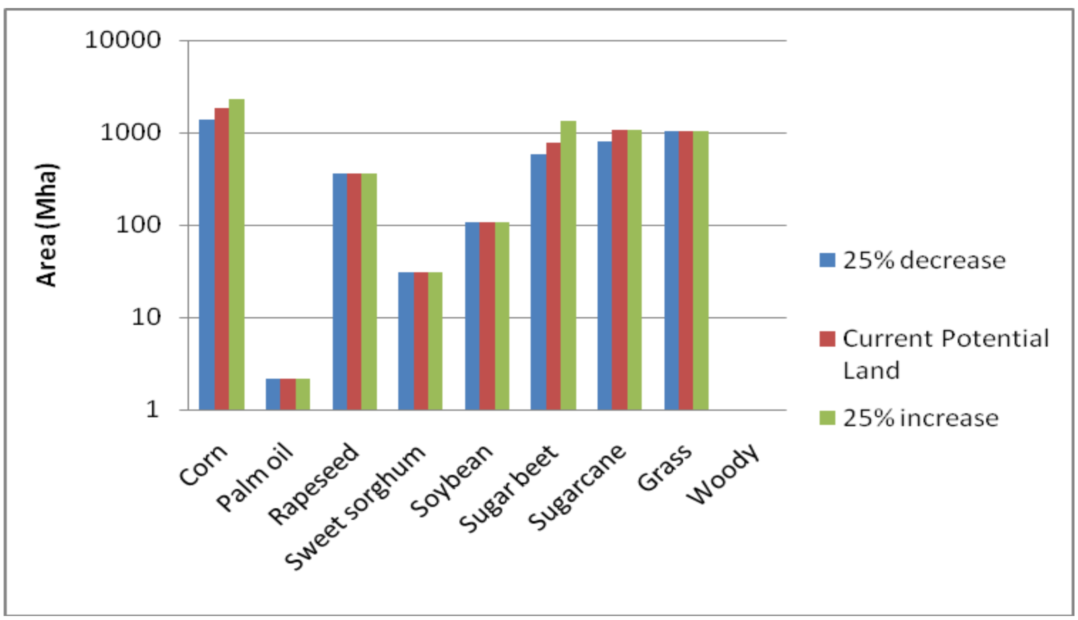

Figure 4.7: Summary of the sensitivity of the optimum land area for selected crop types to potential crop land area

From the results of constraint sensitivity analysis with potential crop land area, palm oil and grasses will be better to grow for biofuel production when the potential crop land area changes.

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CHAPTER FIVE

CONCLUSION

Biofuel energy is an alternative energy that reduces pressure on fossil fuel demand and is also good for the environment. However, the main biofuel feedstocks also serve for food and feed consumption and come from agricultural crops that are grown on land that is limited. Area for biofuel may compete with areas for food and feed consumption, which will cause food and energy insecurity. This study tries to solve this problem by balancing the allocation between food and feed areas and biofuel areas. The optimization model is a good approach to determine the optimum potential land area of the world to use in biofuel production without affecting food and feed consumption. The maximum energy production is calculated based on constraints that do not affect area for food and feed consumption. The optimum crop land area and crop types are obtained based on the maximum energy production given the constraints. This study has an assumption that unprotected grass and woody and forest lands can be converted to cultivated land. The total optimum proportion of land area for biofuel energy, 4,926.49 Mha, consists of corn, rapeseed, sugar beet, sugar cane, and grasses. When considering energy conversion efficiency, the maximum energy production is 520.5 EJ. Of this amount, 5.9 EJ can be identified with food and feed energy; while 514.6 EJ can be identified with biofuel energy. This result is the theoretical value to illustrate the global potential of land area for biofuel. The biofuel energy production per area of land in this study is calculated to be 0.12 EJ/Mha. Also, this study includes other scenarios based on ecosystem concerns in destroying the unprotected grass and woody and forest lands. With respective to the limitation in the degree of invasion by grass and woody land and forest land areas, if it is not more than 10 percent, biofuel energy production can serve about 72 percent of energy demand for transportation. The total optimum land area in this scenario is about 45 percent of the global cultivated land area.

There are many uncertainties that affect energy production and land area allocation. Sensitivity analysis is a method to discover the relationship between input and output variables in the model and useful for policy makers in decision making. The results show that the land area of corn, sweet sorghum, sugarcane, grass, and woody crops is sensitive to energy content. The land area of palm oil, sweet sorghum and soybeans is sensitive to the land area for food and feed consumption. The land area of corn, sugar beet, and sugarcane is sensitive to the potential crop land area.

The optimization model is a good method to solve the problem about resource allocation. This study, done at the global level, can also apply in local areas by using local constraints. Subsequently, the global biofuel energy production per area is useful for comparison with local areas.

A further study should be done at the local level and more factors should be included, such as the economic aspect, government policy, land suitability etc. that provide more realistic results that can be used by policy makers.

APPENDICES

Appendix A

Crop Yield by Selected Crops

Crops	Crop Yield (kg/ha)		
	Minimum	**Average**	**Maximum**
Edible Crops			
• Corn	8,000	12,000	14,500
• Palm Oil	19,000	25,000	44,000
• Rapeseed	1,600	2,400	3,800
• Sweet Sorghum	22,000	26,500	32,000
• Soybean	1,800	2,500	3,000
• Sugar Beet	45,800	60,900	84,300
• Sugarcane	63,300	78,700	98,400
Non-edible Crops			
Grasses			
• Switchgrass	8,000	10,000	18,000
• Miscanthus	6,500	22,000	30,000
Woody trees			
• Silver Birch	12,300	15,800	22,800
• Poplar	3,000	9,500	15,000
• Willow	3,500	10,000	15,000

Source: Miller, 2010

Appendix B

The Amount of Consumption by Selected Crops in 2009

(Unit: 1,000 Tons)

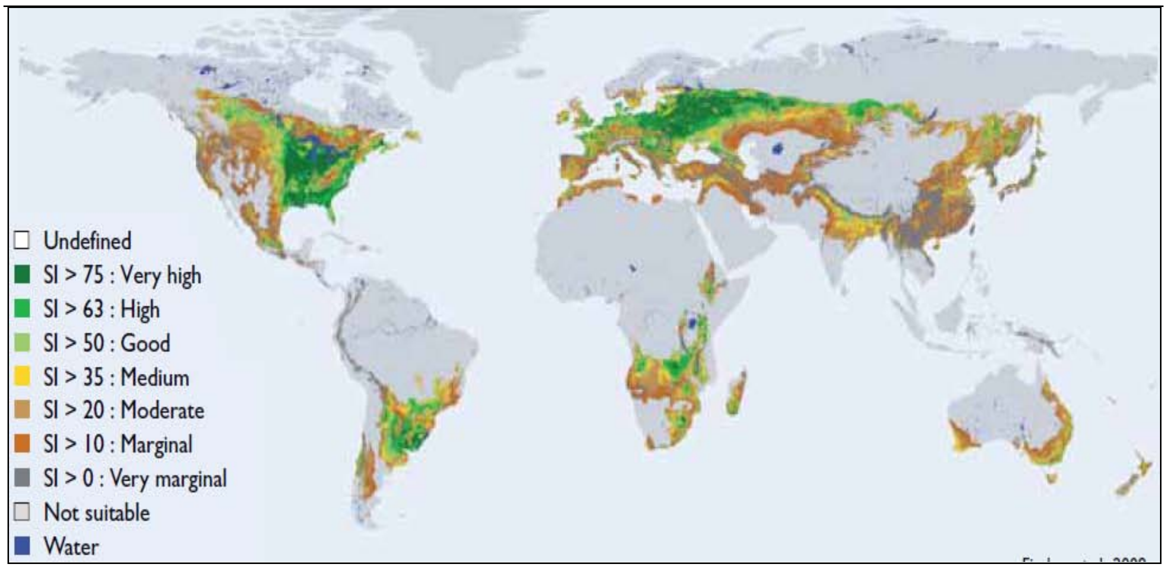
Crops	Consumption					
	Food	Feed	Seed	Waste	Other utility	Total
Corn	113,212.97	477,989.24	5,931.84	81,997.07	78,339.85	757,470.97
Palm Oil	14,464.078	0	0	393.49	28,968.97	43,826.54
Rapeseed	10,838.90	4,344.77	613.266	47,297.88	10,675.64	73,770.45
Sweet Sorghum	26,966.74	28,414.91	907.39	2,745.73	3,354.07	62,388.84
Soybean	37,008.41	7,484.89	7,111.16	207,145.76	141,36.51	272,886.74
Sugar Beet	33.86	10,629.14	0	234,017.84	8,418.69	253,099.53
Sugarcane	24,924.62	27,465.24	28,200.15	1,514,287.0	71,990.89	1,666,867.7

Source: FAOSTAT, 2010

Appendix C

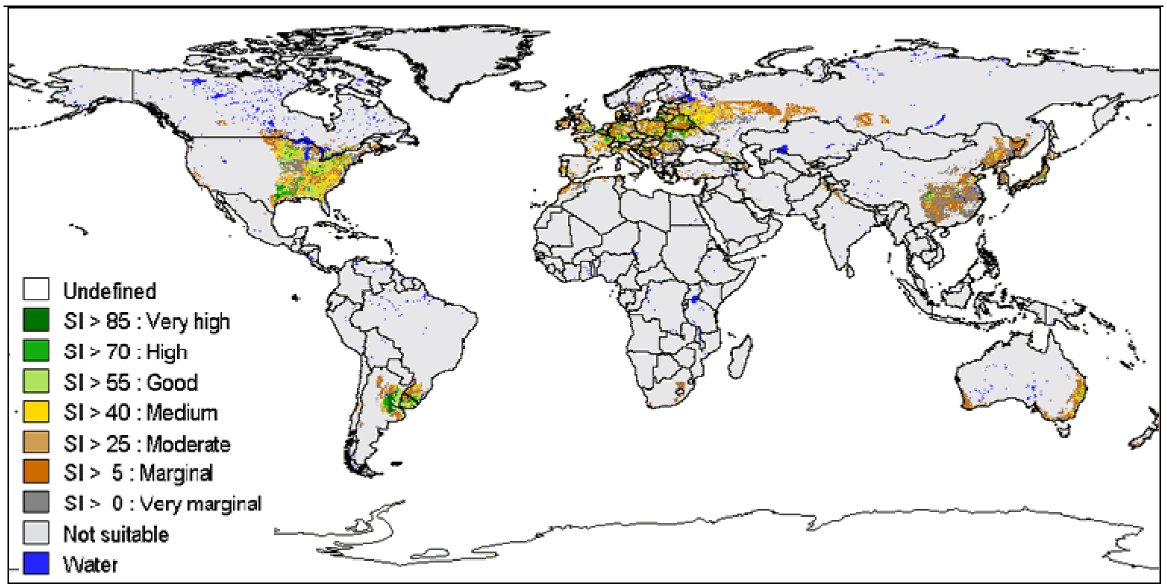
Global Potential Land Area of Selected Crops

Global Potential Land Area for Rapeseed



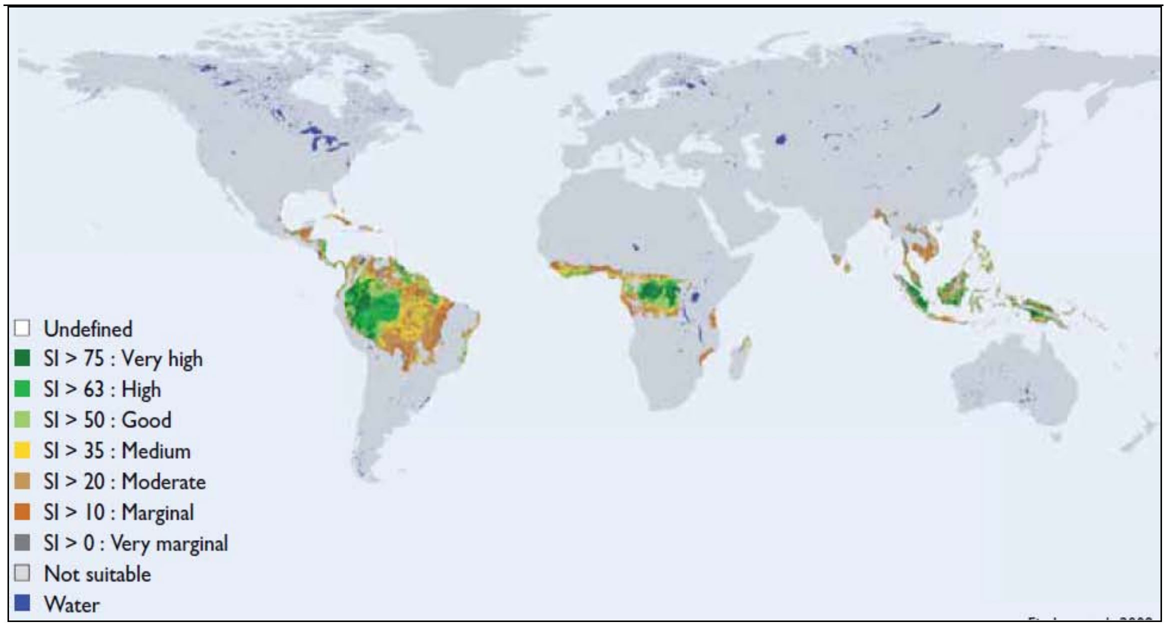
Source: OPEC Fund for International Development, 2009

Global Potential Land Area for Sugar beet



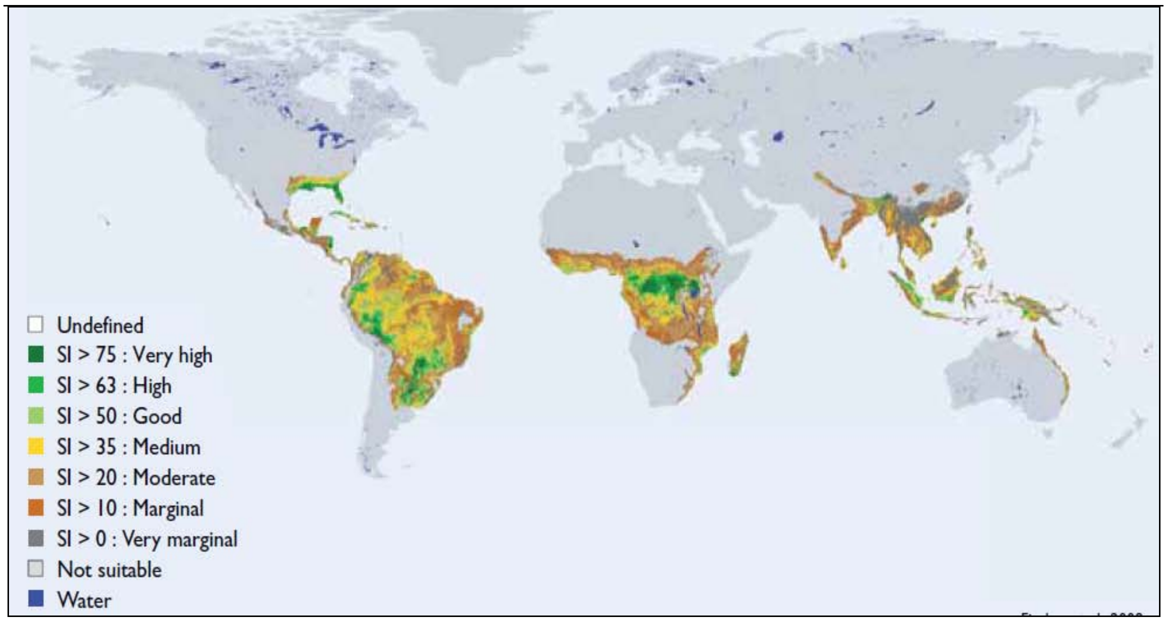
Source: Fischer et al., 2002

Global Potential Land Area for Palm oil



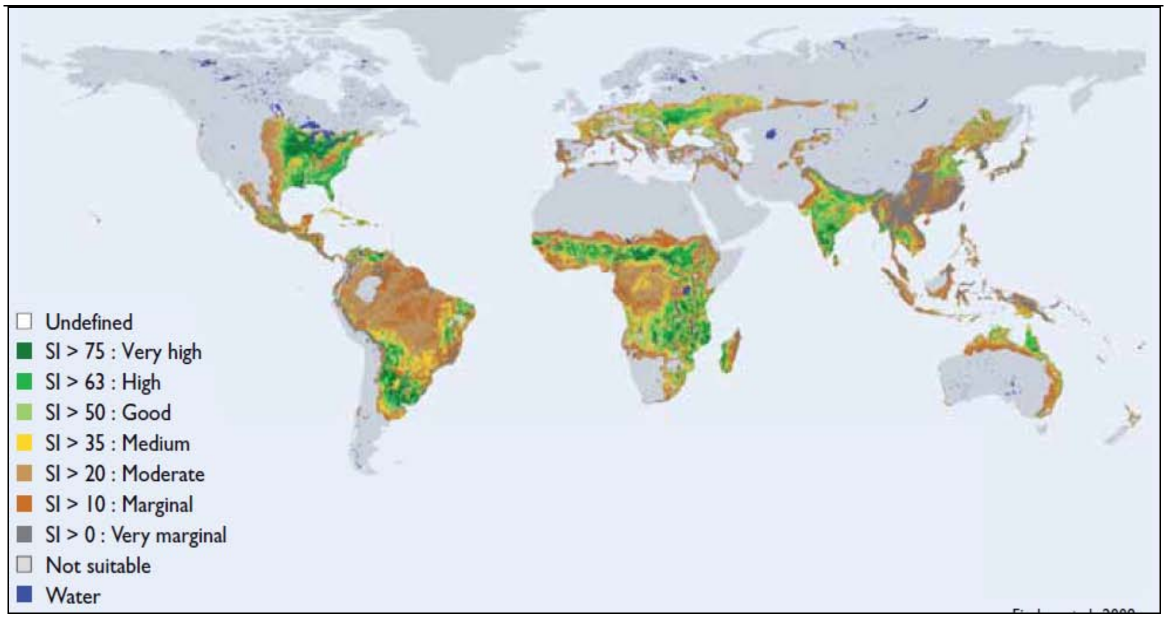
Source: OPEC Fund for International Development, 2009

Global Potential Land Area for sugarcane



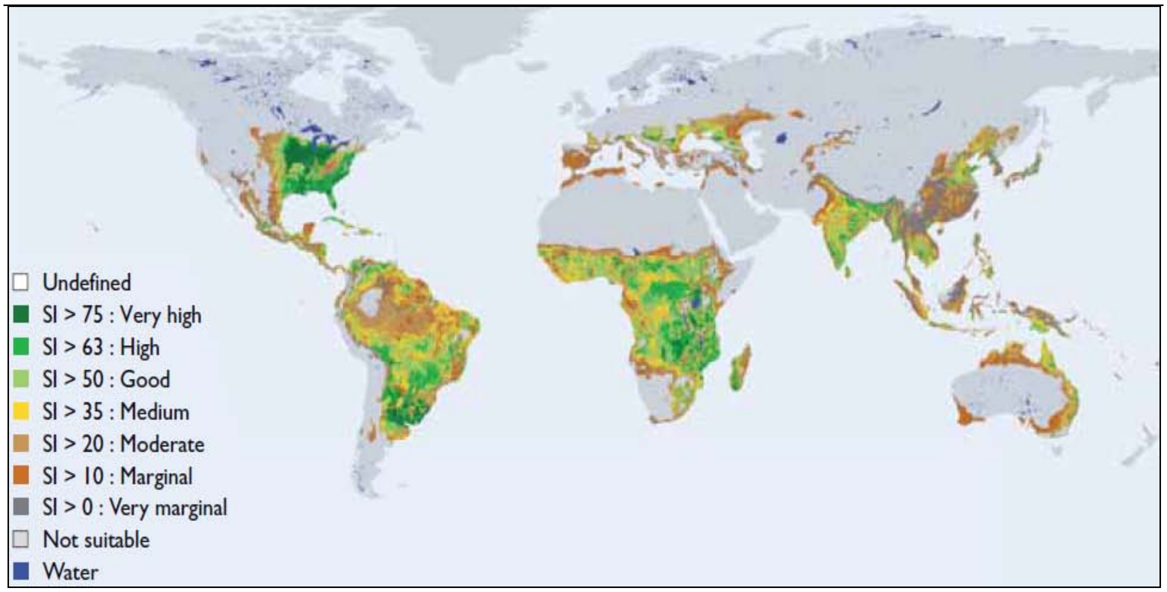
Source: OPEC Fund for International Development, 2009

Global Potential Land Area for Corn



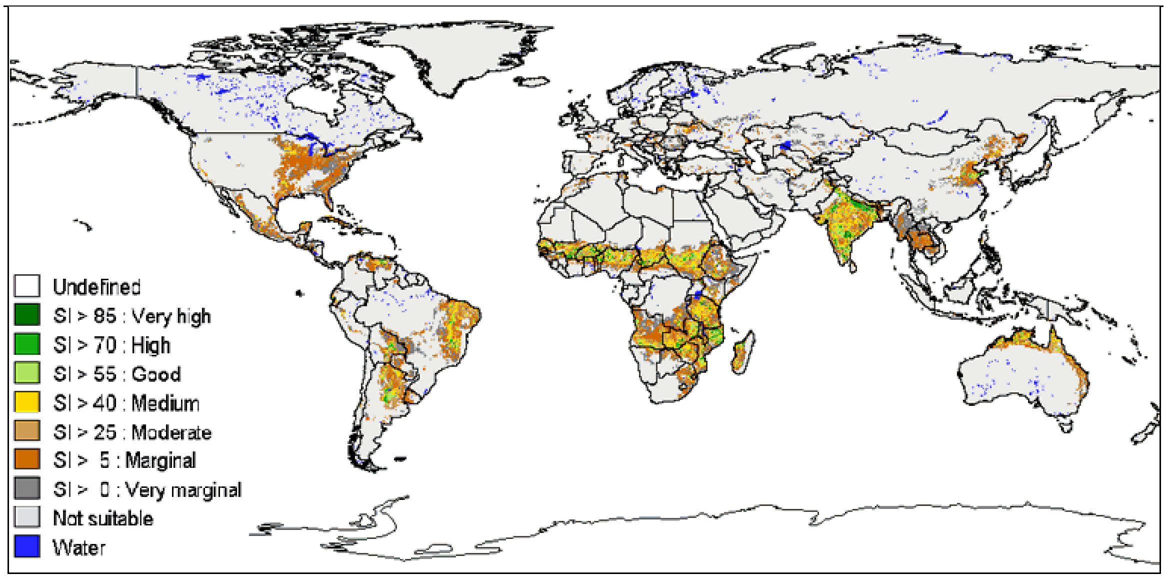
Source: OPEC Fund for International Development, 2009

Global Potential Land Area for Soybean



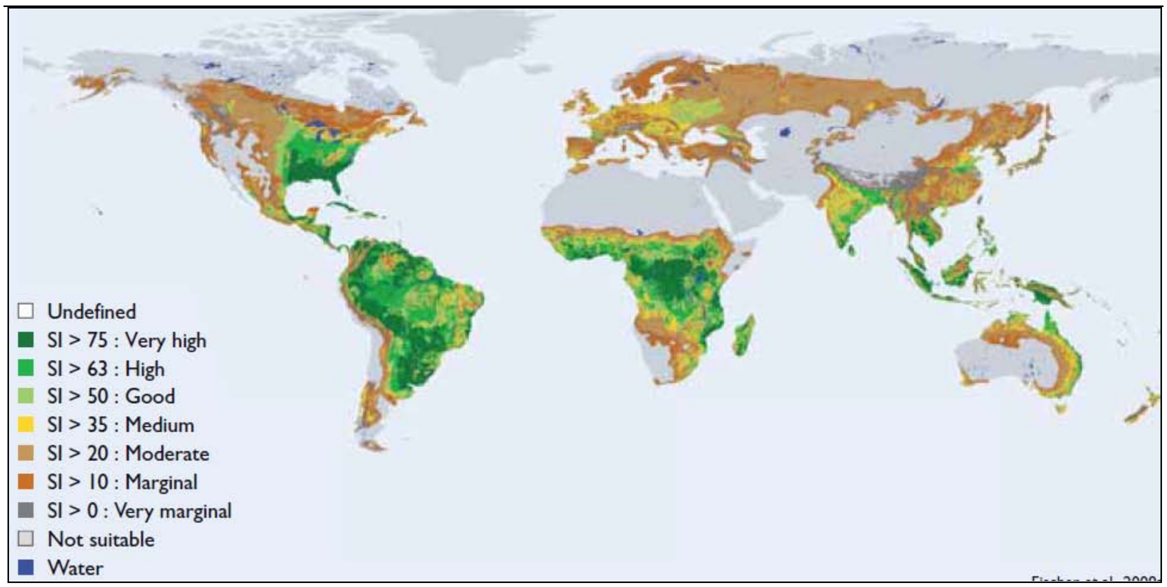
Source: OPEC Fund for International Development, 2009

Global Potential Land Area for Sweet sorghum



Source: Fischer et al., 2002

Global Potential Land Area for Non-edible crops (grasses and woody trees)



Source: OPEC Fund for International Development, 2009